Wingship Investigation

VOLUME 3

Technology Roadmap

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13. ABSTRACT *(Maximum 200 words)*

The Advanced Research Projects Agency (ARPA) has completed an investigation of Wingship concepts and technologies to examine their relevance and utility in future defense applications. A select team of technical experts from U.S. Government and industry was formed by ARPA to assess Wingship-related technologies and mission applications. The diverse group was comprised of Western experts in Wingship-unique and related technologies, including flight controls, aerodynamics, hydrodynamics, propulsion, and advanced structures. Transportation specialists and other mission analysts also participated. The Wingship Investigation concluded that vehicles approaching the efficiency and capacity required for strategic heavy lift are about 10 times larger (in gross weight) than any existing Wingship or other flying water-based craft, and about five-times larger than most experienced Russian or American experts recommend building using current technology. The study concluded that, while the cost and technical risks of developing these very large Wingships are currently unacceptable, there may be some promising military applications for Wingships in the 400- to 1000-ton range. Experience with these relatively smaller vehicles could also permit a growth path for the technology.

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Acknowledgments

Several authors cooperated to write this report. There were writing assignments by topic and section. The team of writers deliberately included talented people with different backgrounds. Inevitably, there were differences in writing style and emphasis between the various writers. Also, the writers had different experiences during the investigation. For example, not all writers visited Russia. There was a fair amount of communication and cross-reading between writers. And, in the final event, a smaller team edited the whole document to fill in transitions, remove contradictions and make the style more uniform. Consequently, the material in each section is not exclusively attributable to a single individual. The following paragraphs, in alphabetical order by author name, describe each authors contribution.

Air Force Colonel Michael S. Francis managed the Congressionally directed investigation for the Advanced Research Projects Agency (ARPA) that produced this technology roadmap. He provided the leadership and executive guidance for the entire investigation and suggested this roadmap as a useful document.

Hugh Anderson wrote the sensors roadmap. Loraine Johnson assisted. Hugh and Loraine are SAIC employees based in Seattle.

Jann Cassady wrote the takeoff technology roadmap with generous inputs from Steve Wells and Daniel Savitsky. Jann is an SAIC employee based in Seattle.

Roger Gallington suggested initial document outlines, and wrote various transition sections such as introductions, summaries and results. He wrote the section on design methodology. He used comments of several outside reviewers to edit the report. He wrote some of the material on Power Augmented Ram (PAR). Roger is a SAIC employee based in Seattle.

Joseph Gera wrote the material on simulation and modeling. Joe Gera is on the senior technical staff of the Dryden Flight Test Center.

Dick Jones wrote the fight test material with inputs from the six roadmaps. Dick Jones is a SRS technologies employee based in Arlington, Virginia.

Eric Lister wrote all the propulsion material. He relentlessly sought out propulsion related issues and solutions. Eric courageously produced the earliest draft of his sections and served as a pathfinder for others. Eric Lister in a Veda Corporation employee.

John Meyer wrote the structures and actuators roadmaps. As the investigation progressed, it became evident that the major uncertainties in structures related to loads during take off and landing. In response, John collaborated with Dan Savitsky to emphasize the importance of hydrodynamic loads. David McAfee assisted John Meyer on structures. Pete Neal and Gale Sundberg assisted John Meyer on actuators. John Meyer is on the technical staff of the Carderock Division of Naval Surface Weapons Center.

Balusa Rao wrote the summary section on the overall technology roadmap using the data from the other six supporting roadmaps. Rao is a SAIC employee based in Seattle.

C.F. Snyder wrote the mission requirements section with major contributions from Frank Macaulay of BDM Federal and Sam Finch of Lockheed Aeronautical Systems Company.

Acknowledgments

Daniel Savitsky made major contributions to the structures section when it became apparent that the major uncertainly in structures related to hydrodynamic loads during takeoff and landing.

Executive Summary

This planning document is one result of the wingship investigation recently completed by the Advanced Research Projects Agency (ARPA) for the Department of Defense (DOD) at the direction of congress. This plan is intended to guide technology development in the event DOD should decide develop a wingship vehicle.

The roadmap identifies six technology areas important to the design of mission oriented wingships. Three of these areas have the potential to significantly improve wingship performance. They are: propulsion; take off aids; and structural loads. Three other areas are sources of great uncertainty in the design process and progress in these areas would greatly increase the confidence of design. They are: modeling and simulation; sensors; and actuators. Also, there are two functional areas that the development of wingships will greatly influence. They are: design methodology and flight testing. The roadmap also provides rationale for why fundamental developments in aerodynamics, hydrodynamics (except as it influences design loads and takeoff), and stability and control is not necessary.

This roadmap suggests how technology programs might evolve in the event that he US started developing wingships aggressively enough to produce a new design of double the previous gross weight every ten years beginning with a nominally 400-ton design with an initial operational capability in 2005. The roadmap provides notional schedules and costs for the six identified technology areas and indications of how design and flight test functions might change to accommodate wingships.

The technology roadmap covers a total period of 40 years. The first ten years (leading to the design of the first two vehicle sizes) has considerably more detail than the reminder. The estimated cost for the first ten years is $358 million. This cost does not included the design and building of mission capable vehicles. These are development program costs only. It does not include full scale engine development, design, build and test. The majority, by far, of the development costs are propulsion related. Propulsion related development cost are 71% of the total for the first 10 years.

1.0 INTRODUCTION

For the purposes of this roadmap it will not be necessary to build a specific Operational Requirement Document (ORD), but rather to understand the process and objectives.

This document is one of several summarizing the results of a two-year study about general class of vehicles currently called wingships. Wingships are a subset of the more general class of vehicles called "wing in ground effect" craft or WIG. By definition and by design, a WIG depends on the aerodynamic ground effect to enhance its performance. Specifically, a wingship is a water-based WIG and is not amphibious.

1.1 Background

In November 1992, Congress directed the Department of Defense (DoD) to determine whether it had any interest in starting a wingship program. Initially the direction specifically excluded any consideration of mission applications. Subsequently Congress broadened the direction to permit study of mission applications and enabled a much more robust answer to the question. Another study document (Wingship Investigation Final Report) summarizes the tentative answer to that question. The complete answer to the question depends partly on the wingship's technical performance. During the study it became clear that the performance of existing wingships (all Russian) was inadequate to be of much interest to our DoD. Consequently, the study group did three things to improve the expected performance of future wingships: (1) Applying existing and near term Western technology to the most developed Russian configuration type resulted in some performance improvement. (2) The study started a series of small technology investigations concentrating on the problems most limiting the performance. The most important performance limiting problem is the high power required for take off. And, to be complete, (3) the study prepared a plan for future technology development that could further enhance wingship performance.

This document is that plan.

1.2 Objective and Scope of Technology Roadmap

This roadmap seeks to provide the rationale and the initial plans for a Concept Formulation (6.2) technology program to systematically develop the technology uniquely related to improving the expected performance and utility of wingships, and the accuracy with which that performance and utility can be predicted. The technical scope of this roadmap is comprehensive — it says something about all the technologies relevant to wingships. However, some subjects are detailed than others. The six more detailed subjects are those the study team believed were significant for the following reasons: (1) they are significantly unique to wingships; (2) they exhibit significant technical uncertainty; and (3) they promise significant performance and utility improvement.

1.3 Methodology of Developing Roadmap

Several underlying assumptions provide structure to this roadmap's development. Expected mission applications, and the anticipated maximum technology development rate, the minimum sizes that have significant military utility, and the maximum sizes we believed to be "designable" — all influence these underlying assumptions.

Concerning size, there are three conflicting arguments. The most demanding heavy-lift long range missions require very large vehicles — on the order of 10 million pounds gross weight — to achieve overall

transport efficiencies that significantly exceed aircraft. On the other hand, the maximum gross weight wingship built for any operational concept demonstration is the Russian LUN with a gross weight of about .88 million pounds. Additionally, experienced Russian and American designers suggest about 2 million pounds as the maximum weight craft they could design with confidence.

Based on these considerations and for purposes of guiding the development of the technology roadmap, we assumed that there would be four mission oriented craft (with each of the last three being about two times heavier than its predecessor).

The first craft would roughly match the size of the current Russian LUN. A reason for starting at the LUN size is that it has not yet proved its military utility and the incorporation of new technology could make significant improvements. Developing a utilitarian LUN sized craft would certainly motivate further development. Further, the Russian LUN design has successfully addressed many first order concerns of skeptics. The LUN serves as an existence proof that wingship construction of this size is practical.

The second craft design would weigh about 2 million pounds, the third would weigh about 4.6 million pounds, and the last in the series would weigh about 10 million pounds. Further we assumed that these craft design would follow each other at roughly ten year intervals. The first craft (400T) would be designed by 1997 to 1998, to be built by 2001. If the program received a go ahead in 1995, it would be followed by the second, third and fourth craft in ten-year intervals, assuming missions were found for each size.

Because engine developments are so long, evolutionary and expensive, we assumed that the powering options for the first two sizes would be derivatives of aviation types.

1.4 Technology Program

This technology program emphasizes and has plans for only six technical areas: Takeoff and Landing Technologies, Propulsion, Structures, Sensors and Navigation, Actuators, and Modeling and Simulation. Section 3 contains a plan for each of these technical areas. However, of these six, only three were judged to have sufficient uncertainty that issues associated with them must be resolved early, i.e. in Concept Formulation (6.2) These three technologies are:

1) Takeoff and Landing Technologies

2) Propulsion

3) Structures

Development work in the other three areas must be accomplished but their issues are less pressing and can be delayed until after the first three are out of Concept Formulation (6.2). Moreover, the second three areas cannot proceed until the uncertainty in the first critical three is reduced. Besides, the short wait of two to five years may enhance their state-of-the-art.

1.5 Items Also Delayed Until Engineering Development

Conspicuous by their absence are aerodynamics, hydrodynamics, and stability and control. These, which are needed for the vehicle, were in the initial Wingship Technical Evaluation Team (WTET) program but

were not seen at the outset of the roadmap development to merit inclusion until Full Scale Engineering Development (6.4). Each is discussed below.

The steady state aerodynamics of wingships in cruise flights is now quite tractable and well understood. Various analyses and experiments have steadily contributed to this area for the past 60 years. Empirical relations for estimating the performance of wingships are not as good as those for conventional aircraft; however, they are adequate to estimate the sizes and proportions of craft to perform specific missions. The advent of "production line" numerical methods has further added to the capability and enabled very accurate computation of the steady aerodynamics during the iterative design process.

The unsteady aerodynamics of wingships is not as well developed. This lack of development primarily results from the fact that there is one more source of unsteadiness in the wingship case when compared to aircraft. In aircraft, unsteady aerodynamics results either from air motion (gusts) or from craft motion (maneuvering or flutter). In strongly ground effected flight, the time varying contour of the water's surface also results in unsteady flow. For example, the flight of a wingship in still air over a fixed wavy surface is a true unsteady flow that has no free flight analogy. Another difference is that the turbulence spectrum is coupled to the water surface thus altering its statistical description compared to turbulence at higher altitudes.

Using aircraft and hydrofoils as examples, we believe that craft designs will generally be based on steady flow aerodynamics with margins applied to cover the environment's statistical nature. Examples of this approach include stall margins for aircraft and cavitation margins for hydrofoils. Some wingship unsteady phenomena, such as resonant motion over wave, are just now tractable with the latest unsteady Computational Fluid Dynamics (CFD) codes. In any event, these codes are available to solve wingship's unique unsteady problems as they occur. It does not seem that the future of wingship design rests heavily on further developments in the general understanding of unsteady flow.

Hydrodynamics permeates many aspects of wingship design. This technology roadmap document does not suggest a general technology program in hydrodynamics because it is so design dependent. There is much hydrodynamics development as an essential part of take off technology and as an essential part of structures and loads. Also, hydrodynamics is the key technology in achieving acceptable habitability during loiter on the sea surface, and the design methodology described in Section 4 incorporates habitability. Design studies will suggest specific hydrodynamic developments.

It is easy to show that during wingship cruise, the pressure induced displacements of the water are so small that they have negligible effect on aerodynamics. At the lower speeds associated with take off and landing, the dynamic pressure of the air is negligible compared to that of the water. Combined aerohydrodynamic effects are most important during the higher speed parts of take off and landing where planing, spray, impacts, and craft dynamics are all involved. Again, these interactions are so design dependent that it is not practical to define an effective general hydrodynamics development program.

The extreme importance of takeoff and landing to wingship design justifies a separate chapter mainly on the aerodynamics of their multi-disciplinary processes. Figure 1-1 is a matrix showing how the five technologies discussed in this roadmap relate to the takeoff and landing issue.

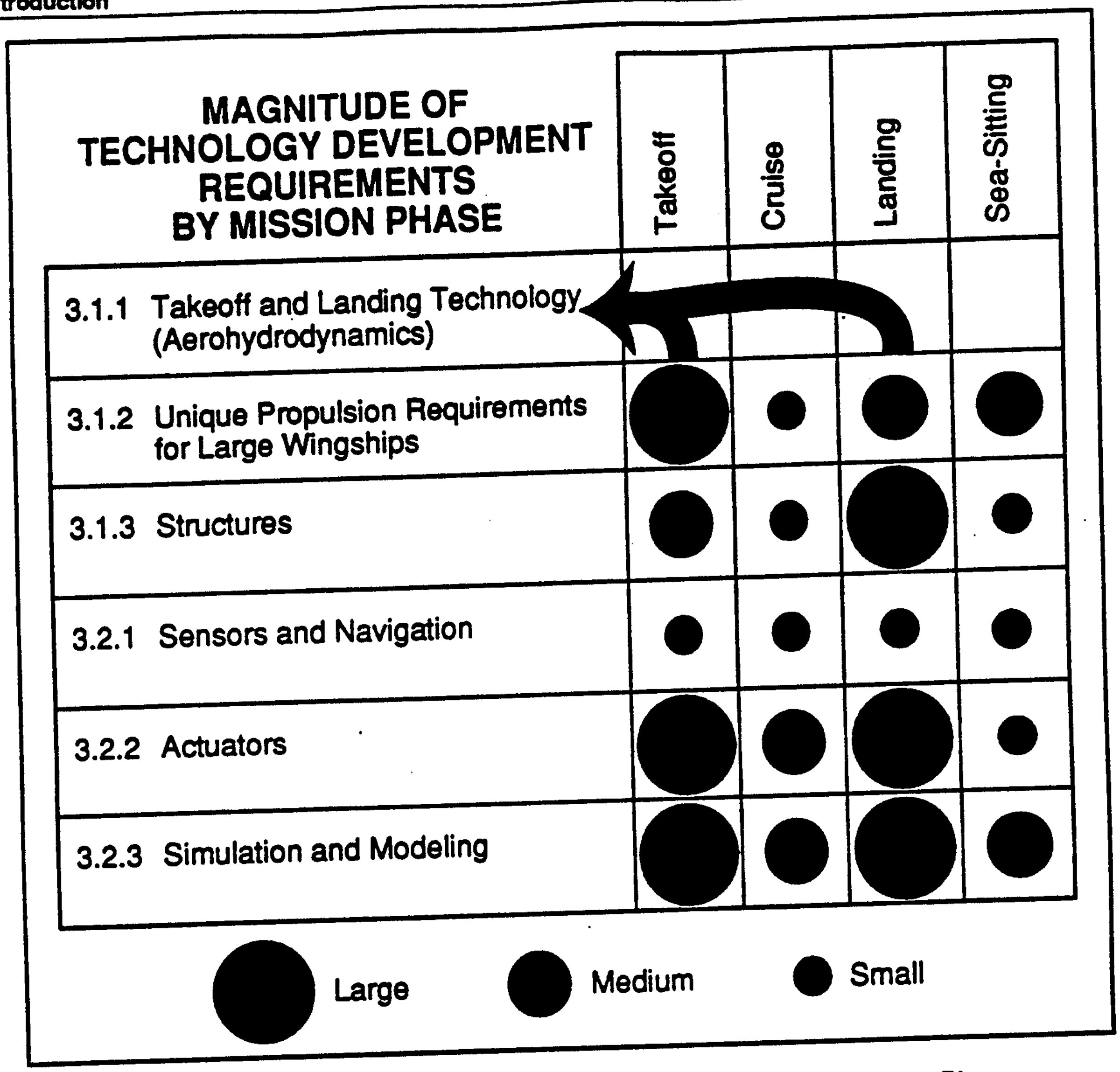


Figure 1-1 - Magnitude of Technology Development Requirements by Mission Phase

Stability and control — especially longitudinal motion — in ground effect challenged designers for some time and was the focus of much early work. Having reviewed the literature carefully, talked to the Russian designers and analysts, and converted their results into our engineering terms we believe we understand this area rather well and do not believe that further fundamental research in this area would significantly improve future wingship design and performance. Therefore, this roadmap does not include a plan to develop technology in stability and control. However, the simulation plan, flight test plan, and navigation and sensors plan each contain information that borders on the stability and control area. Taken together, these plans adequately address the most important parts of stability and control.

In parallel with the unsteady aerodynamics area, craft design will probably and initially be guided by classic methods of linearization augmented with simulation using non-linear force and moment derivatives. A recent example of the success of this approach it the X-31 program which succeeded in accurately controlling flight with all these unpleasant features except ground effect. Because of the statistically random nature of water waves and turbulence, the non-linearity of the rigid body in still air, and the fact that real

unsteady flows have hysteresis (dynamic stall for example); the most robust way through these problems seems to be simulations tailored to match flight test data. While this approach doesn't build understanding of why things happen, it does facilitate confident vehicle design From a stability and control point of view, our opinion is that nominally steady flight in ground effect is simpler than the X-31.

2. OPERATIONAL REQUIREMENTS DETERMINATION

With wingships, as with all other military hardware systems, procurement starts with an unfilled need outlined in a Mission Need Statement (MNS). The MNS comes from the operational community and is the basis for an Operational Requirement Document (ORD) which is prepared by the cognizant acquisition agency for approval by the sponsoring service(s). The ORD is composed of:

- General Description of Operational Capability
- Threat
- Shortcomings of Existing Systems
- Capabilities Required
  - System Performance
  - Logistics and Readiness
  - Critical System Performance
- Integrated Logistics System (ILS)
- Infrastructure Support and Interoperability
- Force Structure
- Schedule Considerations

For the purposes of this roadmap it will not be necessary to build a specific ORD, but rather to understand the process and objectives.

2.1 Objective

The objective of the Operational Requirements Determination process is to generate a set of performance parameters based on operational needs which will define a mission-oriented wingship. Range, sea-sitting capability, load capacity, weapons or avionics capabilities, and low-observable characteristics are all operational demands which, to a great degree, dictate the vehicle size and configuration. The vehicle size and configuration will in turn determine propulsion, structural and mission-oriented requirements. Analysis of the potential mission areas for which wingships might be considered suitable will yield these operational drivers.

2.2 Methodology

The evolution of a system design begins with the refining of system requirements as shown in Figure 2-1. This process provides the basis for making informed tradeoff decisions, given affordability constraints and user needs. It allows for a smooth translation of user needs into alternative concepts from which a final design can be filtered. The final operational design is then married with state-of-the-art and emerging technology to produce a production design.

To assist in creating notional requirements for the purpose of technologically designing wingships, the following missions were considered: SOC Mk V Boat or Deep Submergence Rescue Vehicle (DSRV) Delivery Vehicle, Cooperative Engagement Concept Ordnance Carrier (CECOC), Amphibious Lift Trans-Oceanic (ALTO) and Heavy Lift. The Delivery Vehicle is representative of a 400-ton vehicle, the CECOC of a 1,000-ton vehicle, the ALTO of a 2,300-ton vehicle, and the Lifter tops the list at 5,000 tons. Given these sizes and mission requirements, it becomes possible to establish each class of vehicle's design criteria. The Delivery Vehicle for example, must have the ability to carry the payload craft as well as launch and

recover it from the water. The CECOC must be configured around the payload VLS installation and so forth.

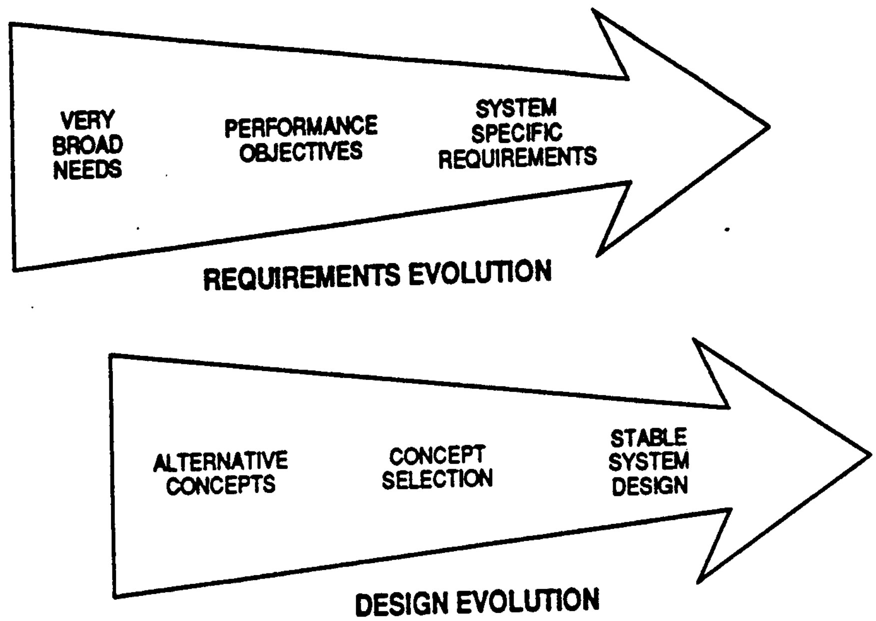


Figure 2-1 - Evolutionary Flow Process

Once a design is started, technology issues can be addressed as they are encountered. Are engines with sufficient power available? If not, what must be developed? Do existing structural methods support the fabrication of the design? As these questions arise during the design of the first vehicle, the flight test program for the *Spasatel* should be generating empirical data which will help provide answers. The parallel design and test for the 400-ton class vehicles should complement each other. The design team provides requirements issues and the test team provides performance results. The difference between the requirements and the demonstrated performance defines the technology deficiency that must be overcome to successfully build a mission capable wingship. This technology deficiency establishes the program risk factor.

2.3 Mission Opportunities

The Wingship Mission Analysis Team (WMAT) is composed of private companies and DoD agencies. The team is headed by Carderock Division, Naval Surface Warfare Center (CDNSWC), the team's mission is to assess potential military application for WIG vehicles. Other participants include BDM Federal Inc.; Lockheed Aeronautical Systems Company; Military Traffic Management Command, Transportation Engineering Agency (MTMCTEA); Naval Air Warfare Center, Warminster (NAWCADWAR); and Naval Surface Warfare Center, Dahlgren Division, White Oak Detachment (NSWCWO). The analytical tools used to assess areas of possible military utility included; combat simulation, defense transportation analysis, military mission analysis, and life cycle cost estimating. WMAT shared the results of their studies and identified possible civil and commercial applications for WIG technologies.

This initial mission analysis of wingships employed in several military, civil and commercial applications went on for several months. The team screened, then selected a small number of applications for further

investigation to allow two-way interaction with the technology team. In this way, mission driven technical requirements can be identified and the probability of meeting them examined.

2.3.1 Potential Missions

The following missions were analyzed during the previous efforts and considered for further work.

MILITARY:		
General Military Heavy Lift for Deployment	Amphibious Lift-Trans Oceanic (ALTO)	Airborne Shallow Water Mine Warfare (ASWMW)
Air Defense Mission	Airborne Anti-Submarine Offensive Mine Delivery Warfare (ASW)	Special Operations Carrier
Airborne Mine Countermeasures (AMCM)	Theater Missile Defense (TMD) to include Tactical Ballistic Missiles and Cruise Missiles.	Airborne Shallow Water ASW $(ASW)^2$
Amphibious Lift-Ship to Shore (ALSS)	NAVAL Tactical Missile (NTACMs)	Cooperative Engagement Concept Ordnance Carrier (CECOC)
Time Critical At Sea Replenishment	DSRV Operations	
CIVIL AND COMMERCIAL:		
Civilian Law Enforcement Drug Interdiction Vehicle	Coast Guard Patrol and Search and Rescue	Customs and Immigration Patrol (CIP)
Disaster Response	High Speed Automobile Ferry (HSAF)	Out-Sized Commercial Cargo Transport (OCCT)

2.3.2 Attributes and Rating Factors

A Multi-Attribute Utility Analysis method was used to rank and prioritize the missions. Figure 2-2 shows the system structure. Discussion of definition and rating instructions follow the figure.

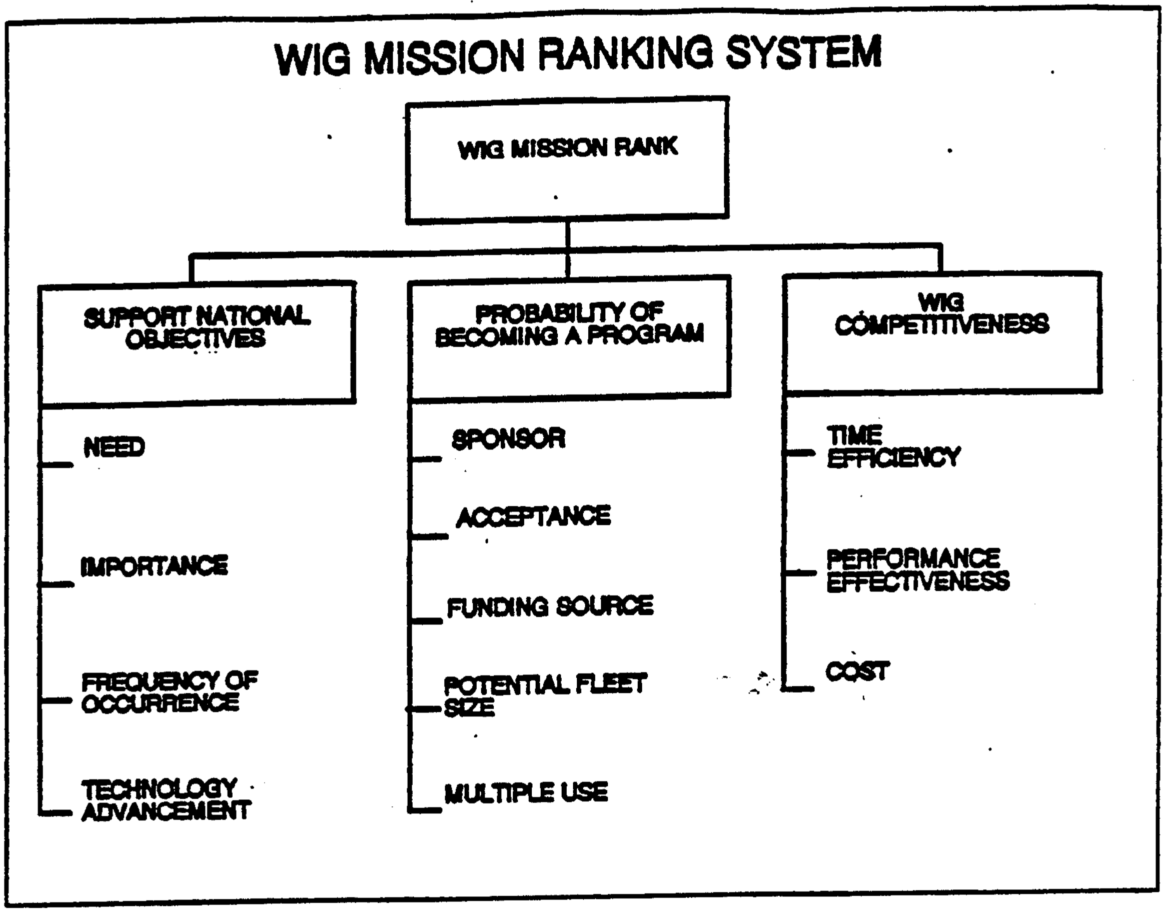


Figure 2-2 - Factors and relative weights for multi-attribute utility analysis of wingship applications.

2.3.2.1 Overall Analysis Information

Only the importance of the particular WIG mission was considered for evaluating Support of National Objectives and Probability of Becoming a Program. How well and how cost-effectively a WIG could do the mission with respect to competing systems was evaluated qualitatively in the WIG Competitiveness section.

SUPPORT NATIONAL OBJECTIVES

1. **Need** - Does the WIG mission support attainment of national objectives?

- Defense of the homeland
- Economic well being
- Spread of democratic ideals, priorities, and sphere of influence
- Support of friends and allies

2. **Importance** - How important is this mission to achieving national objectives?
3. **Frequency of Occurrence**

Military — How many operations will use this mission during a WIG's 25 year lifetime? The more probable the need to accomplish a mission, the

	more likely there is to be funding to develop a tool to accomplish the mission.
Civilian	How many franchises or service routes would there be for this type of vehicle?
Patrol/Disaster Response	How many operational patrol sites or bases would there be for this type of vehicle? How many times would a response be required?

4. **Technology Advancement Required** - Will technology development be required to accomplish this mission? This does not include the technology development required to develop the basic WIG. This is related to mission-specific systems that would be installed on the basic vehicle. (e.g. For the Fire Support Mission will we be able to use the standard MLRS or Cruise Missile launchers or will special ones need to be developed?)

PROBABILITY OF BECOMING A PROGRAM

1. **Sponsor** - Is there an individual or group that believes the WIG mission offers such an advantage to their ability to accomplish objectives that they are willing to sponsor initial development and construction by stating that they would use the WIG if it were available? This could be either a military mission or a commercial enterprise. (e.g. Amphibious Assault or High Speed Auto Ferry)

2. **Acceptance** - For the mission being considered, will the WIG be accepted as a serious competitor? Is there some event or perception within the community that would operate the WIG for this mission that would make them reluctant to trust and/or use it?

3. **Funding Source** - Is the individual or group that wants to use the WIG willing to fund some or all of the development cost? Is there an organization such as Advanced Research Projects Agency (ARPA) that would fund initial development for a group of potential users?

4. **Potential Fleet Size** - What is the size of the fleet that will be built to support this mission? This would be a production run with virtually no changes during the production lot.

5. **Multiple Use** - Can the configuration that is designed and sized to accomplish this mission be used for another mission with minimal changes. (e.g.. A vehicle sized to do the Drug Interdiction mission would easily be converted to the Coastal Patrol and Search and Rescue missions.)

WIG COMPETITIVENESS

1. **Time Efficiency** - Does the WIG reduce the overall time required to accomplish the mission? How important is the response time reduction achieved by using a WIG to the overall success of the mission? (e.g. For an oil spill the sooner cleanup can begin, the better the results.)

2. **Performance Effectiveness** - How well does the WIG do the mission in comparison to other methods of doing the mission? Is there any real advantage to doing the job with the WIG?

3. **Cost** - How expensive is the WIG to purchase with respect to a competing system? Is the WIG more expensive to operate or less expensive to operate than the competing system?

2.3.3 Selected Missions

The evaluation resulted in three basic categories of applications for further analysis.

- Combat Missions
- Transport Missions

- Missions which support civilian law enforcement or disaster relief

The specific applications given the highest priorities for further development were (in alphabetical order):

- Amphibious Warfare Lift (MEU sized)
- Civil Applications
  - Auto Ferry
  - SAR
  - Law enforcement
  - Disaster relief
- Mine Warfare
- Multi-mission/cooperative engagement
  - Strike missile carrier
  - Air/TMD defense carrier
- Special operations carrier
  - SOF lift (Mk V, ASDS and etc.
  - insertion/extraction platform

In the follow-on research, the mission were split between three teams; (1) Lockheed Aeronautical Systems Company and NAWCADWAR; (2) BDM Federal and NSWCWO; and (3) MTMCTEA. The heavy-lift missions will not be addressed further as they have been examined in detail. The new focus will address susceptibility and vulnerability of wingships in a hostile environment. Alternate platforms of varied size and configuration performing the previously identified missions will be analyzed. Also, the ground attach and air defense missions will be evaluated with simulation modeling.

2.4 Mission Driven Technologies

The Missions Analysis Team (MAT) methodology for evaluating technology needs combined top-down platform assessments with desired mission operating characteristics. No attempt was made to evaluate specific subsystem and/or technology requirements. Instead, this assessment focused on identifying general development areas that would support or enhance mission performance. The included missions consisted of those identified in the Section 1 as highest priority for further development:

- Lift Support
  - Amphibious warfare lift (Marine Expeditionary Unit size operations)
  - At-sea replenishment
  - DSRV Operations
- Mine Warfare (especially, countermine operations)
  - Sea mine detection and neutralization
  - Obstacle-clearing in support of amphibious operations
- Multi-mission ordnance carrier
  - Strike missile carrier

  - Air/tactical missile defense platform
- Special operations carrier
  - Mark V patrol craft
  - Advanced swimmer delivery system (ASDS)
- Civil applications
  - High-speed auto ferry
  - Law enforcement/border patrol
  - Search and rescue
  - Disaster relief

The general technical requirements list for WIG missions is divided into three major categories in this section: common requirements for the entire range of WIG mission concepts; specialized requirements for military combatant and civil mission applications; and mission-specific technical requirements (if any). The technical roadmap areas (takeoff and landing technologies, propulsion, structures, navigation and sensors, actuators, modeling and simulation) were considered as a guide to identifying requirements, but they were not a limiting factor.

2.4.1 Common WIG technical requirements

Several desired operating characteristics emerged from the MAT assessments for all WIGs regardless of mission. These included:

- **Enhanced takeoff.** The requirement to achieve enhanced capabilities for WIG takeoff is well documented in other roadmap sections. The MAT considered it highly desirable for all WIG applications to achieve some level of smooth flight during takeoff to provide for passenger safety and equipment integrity. The alternative is to harden components and payloads to prevent damage during takeoff and landing.
- **Out of ground effect (OGE) flight:** While specific flight profiles would vary for specific missions, some capability to sustain OGE flight is necessary for collision avoidance and to enhance maneuverability options. Depending on fuel burn rate penalties, sustaining higher altitude flight for long distances (hundreds of miles) might be desirable to shorten necessary transit distances and times. OGE flight is also necessary to support aerial refueling.
- **Sea-sitting.** Stability while sea-sitting is necessary for all WIG applications, for periods of relative immobility, such loading and unloading, harbor maneuvering and loitering near targets. It is desirable to be able to sea-sit in Seastate 3, and desirable for Seastate 4.
- **Infrastructure.** WIG designs should accommodate existing infrastructure as much as is feasible. Some new infrastructure, however, is necessary to support WIG port and at-sea operations. This infrastructure ranges from berthing and support structures, to mundane elements such as fenders, tug contact points, ramps and etc.

2.4.1.1 Military combatant vehicles

- **Quick takeoff.** In addition to providing defensive systems and armament, the WIG platform's inherent speed and mobility is important to limit platform susceptibility. An approximately 60-second takeoff profile to achieve cruise velocity (~200 to ~300 knots) should be sufficient to defeat the

acquisition and strike capabilities of most modern air-to-surface missiles. The takeoff time and cruise velocities should be sufficient to avoid most other sea- and land-based threats to military combatant WIGs.

- **Refuel, rearm and recrew at sea.** Because WIGs may operate as an early entry presence in areas far from friendly resupply facilities, the ability to resupply at sea is desirable Support vessels with appropriate cranes and other equipment may be either WIG-based or standard naval platforms (although WIG-basing would allow simultaneous deployment of combatant and support vessels).
- **Low observability.** Signature reduction (radio frequency, infrared, visual, aural, electromagnetic emissions) are needed for all military applications. Hull shape may make the platform inherently stealthy to some degree, but additional low observable technologies should be incorporated in the military designs.
- **Multi-day habitability.** Many military missions considered require on-station times of several days or longer. Crew accommodations and facilities need appropriate consideration.

2.4.1.2 Civil vehicles

No major design considerations unique to civil WIG applications were identified. However, federal regulations may require special safety considerations need development.

2.4.2 Mission specific technical requirements

- **Payload.** The major design criteria specific to each identified mission revolves around unique payloads and supporting systems. This is not a major WIG design issue.
- **Beaching and unbeaching.** To support amphibious operations, certain disaster relief missions, and obstacle clearing the ability to operate on semi-rough to rough beaches was considered necessary. If this capability could be incorporated into general WIG design, it would enhance the flexibility of the design for use in other missions.

2.4.3 Summary

The MAT concluded that there are useful applications requiring WIG payload, weight and size configurations all of which indicate a vessel design in the 400- to 800-ton range. It is possible that these military and civil applications could be accomplished by variants of a single basic WIG design.

3. IMPORTANT TECHNOLOGIES

Progress in six technological areas would facilitate the confident design of wingships. Progress in three of these six areas would additionally greatly improve wingship performance and, consequently, permit the design of smaller and less expensive vehicles for a given design mission.

In two sub-sections, this major section first presents technology plans for the most important technologies which both improve performance and facilitate design and then presents plans for the other technologies which facilitate design and don't greatly influence performance.

3.1 Technologies Requiring Development

Improvements or uncertainty reduction in three technical areas have the potential to significantly improve the performance of wingships and consequently reduce the size and cost of the vehicle required for any particular design mission. These technical areas are: (1) takeoff; (2) propulsion; and (3) design loads for structure.

3.1.1 Takeoff and Landing Technology

The single greatest impediment to the overall wingship utility is the large power requirement to accelerate a wingship from rest to cruising speed, contrasted with the power requirement for cruising at low altitude. Both wingships and commercial aircraft require two to three times larger thrust during takeoff than during cruise. Commercial aircraft achieve high cruise efficiency by climbing to altitude, where the thrust produced per engine is reduced and nearly matches the low drag of the airplane in cruise. WIG vehicles operate near the water surface to benefit from the ground effect which reduces the induced drag, but the engine thrust is in excess of that required for cruise. The landing phase of wingship operation establishes the structure's peak load requirements. This takeoff and landing technology section presents proposed multidisciplinary vehicle design concepts that may satisfy operational requirements, and overcome takeoff and landing limitations.

3.1.1.1 Technology Requirements

The wingship takeoff and landing operational phases establish many requirements for vehicle design. The requirements imposed by takeoff and landing are presented in other sections of this report because it is these requirements that drive the technology development. Table 3-1 lists requirements imposed by the takeoff and landing operational phases and specifies where the requirements are presented in this report.

Table 3-1 - Requirements Imposed By Takeoff and Landing Operations

REQUIREMENTS IMPOSED BY TAKEOFF AND LANDING OPERATIONS	ROADMAP SECTION
Vehicle must be designed for the number of engines required for takeoff. This results in too many engines for cruise, causing a cruise penalty due to the weight and drag of the extra engines required for takeoff. Approaches other than propulsion technology application or development.	Takeoff and Landing Technology
Vehicle must be designed for the number of engines required for takeoff. This results in too many engines for cruise, causing a cruise penalty due to the weight and drag of the extra engines required for takeoff. Propulsion applications and development.	Propulsion
Noise Abatement: Vehicle is not allowed to exceed certain dB levels on takeoff.	Propulsion
Toxins: Takeoff conditions may result in the emission of dioxins. Some dioxins may be carcinogenic.	Propulsion
Water/Air Separation: Water may splash into the engines during takeoff drastically reducing thrust production.	Propulsion
Peak Loads: Multiple wave impacts during takeoff and landing establish the peak load requirements for the structure.	Structures

3.1.1.2 State of the Art

To date the largest wingships built are made by Russians and use captured air pressure under the wings to augment the dynamic lift of the fuselage in contact with the water and the aerodynamic lift on the wings to achieve liftoff. This captured air pressure is provided by separate, forward-mounted power systems. The specific technique of aiding the takeoff, and perhaps landing, by directing the efflux of forward-mounted propulsion units under the wing is called air injection in Russia and power augmentation or Power Augmented Ram (PAR) in the U.S.

The state of the art of WIG vehicle takeoff can be quantified by reviewing the state of the art of seaplane hull takeoff performance and wing-in-ground effect vehicle takeoff performance, with and without PAR. Seaplanes have more drag than a WIG with PAR and less drag than WIGs without PAR. A comparison of these three vehicle types brackets the state of the art.

Maximum Drag/Weight Values

The hydrodynamic behavior of seaplanes and WIGs can be divided into four regimes: low speed or displacement regime, hump speed regime, planing speed regime, and takeoff speed regime. The maximum drag is usually experienced in the hump speed regime. The focus of takeoff technology development is to reduce maximum drag.

The hump speed regime is the second phase of the takeoff process where hull trim and hydrodynamic drag attain their maximum values. The hull continues to support a major part of the weight (approximately 85%) during this phase (Reference 1, page 4). The hull trim is mainly determined by the step configuration and afterbody design. The aerodynamic trim is still relatively weak, but the thrust and thrust moment about the center of gravity are large.

The Davidson Laboratory at Stevens Institute of Technology has extensively studied seaplane hulls. Based on the results of their experimental work, a well designed seaplane hull, with a load coefficient $K_2 = 0.0166$ for a length to beam ratio of 6.5 has a maximum drag/weight ratio of 0.23 in smooth water as shown in Figure 3-1. The values for this figure were derived from Figure 28 of Reference 1. More recent model tests of a high L/b, double chine vehicle indicate state-of-the-art seaplane hulls have a maximum drag-to-weight ratio of 0.18 (Reference 13).

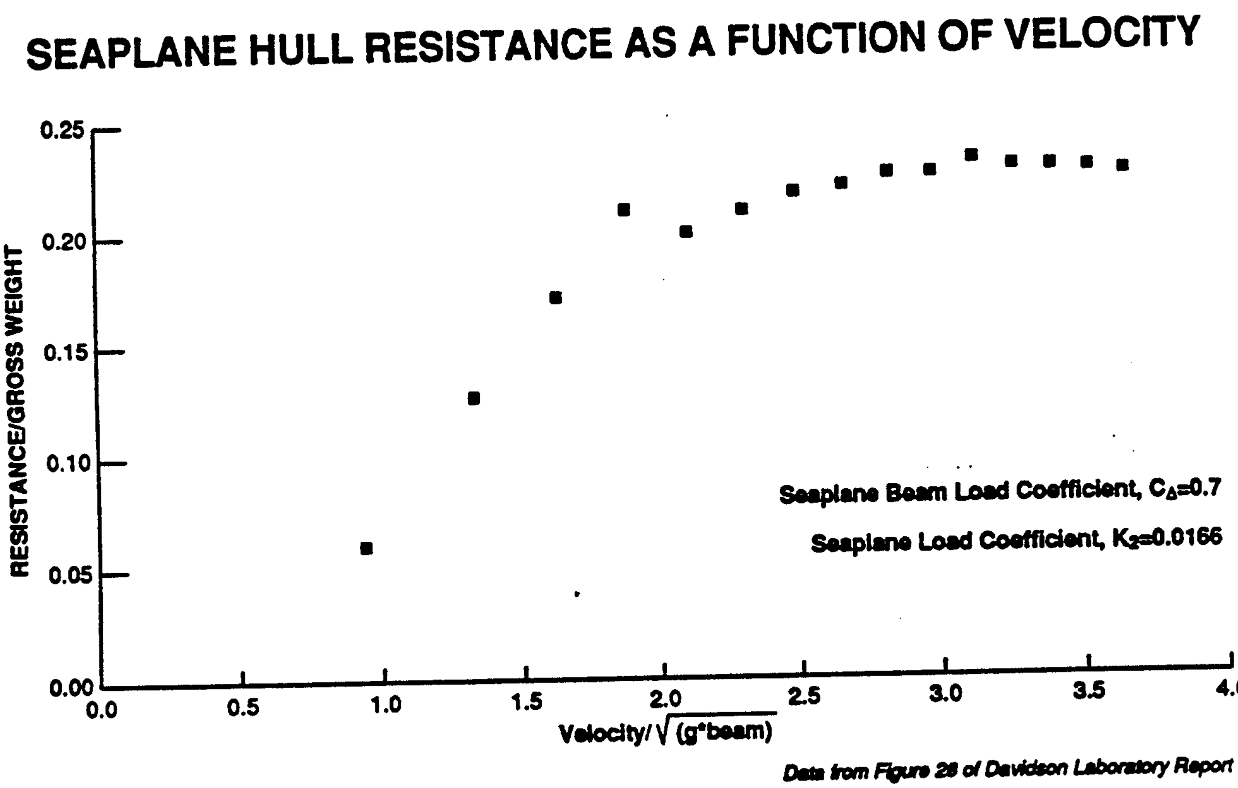


Figure 3-1 - Seaplane Hull Resistance as a Function of Velocity

The Russians have published data on WIG performance with and without PAR. The tested vehicle has a load coefficient of $K_2= 0.04$ and an L/b ratio of 0.32 based on its wing planform and gross weight (Reference 2, pages 13 and 37). (See Appendix A for calculation of K2 and L/b.) Based on the same data, the hull has a length to beam ratio of 11.53 and a loading parameter $K_2 = 0.016$ based on hull dimensions and gross weight. The WIG vehicle with PAR in smooth water had a maximum drag/weight ratio of 0.17 (Reference 3, page WS63), a better value than the comparable value for the seaplane. The WIG vehicle without PAR in smooth water had a maximum drag/weight ratio of 0.36. (Reference 3, page WS63), a value worse than the comparable value for the seaplane. These results are shown in Figure 3-2.

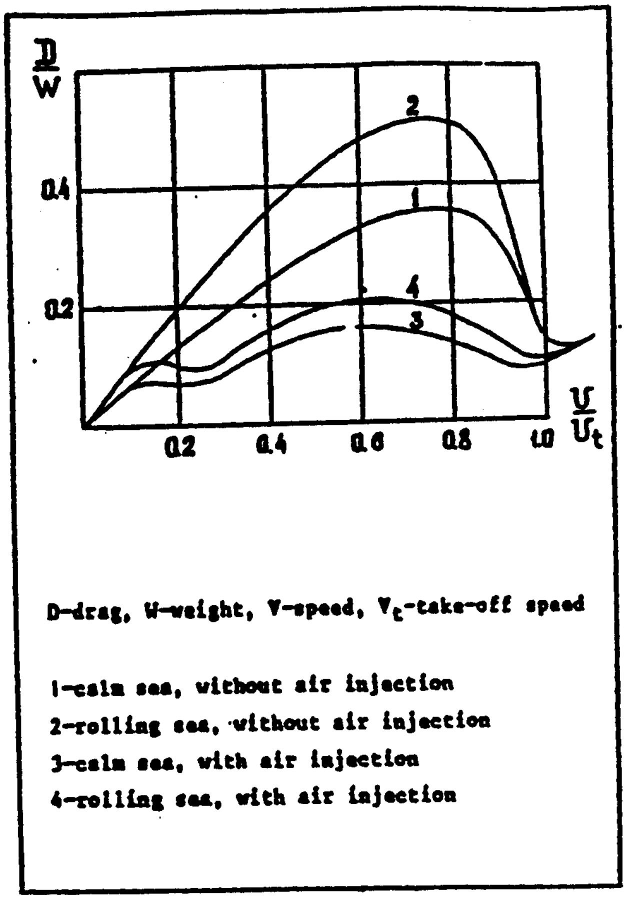


Figure 3-2 - Published Russian Data (Reference 3, page WS63)

Effect of Rough Water

Rough water increases the drag for seaplanes, WIGs with PAR and WIGs without PAR (Figure 3-3). A general rule is that for seastates, where $H_{1/3} = 0.40 \times$ beam, the rough water drag for a seaplane may be 15% greater than the calm water drag (Reference 4, section 5.4.4.3).

Based on Russian data, the rough water (referred to as "rolling seas") drag for a WIG vehicle with PAR is approximately 23.5% greater than the calm water drag, and the rough water drag for a WIG vehicle without PAR is approximately 42% greater than the calm water drag. A WIG vehicle with PAR has the lowest amount of drag for either case.

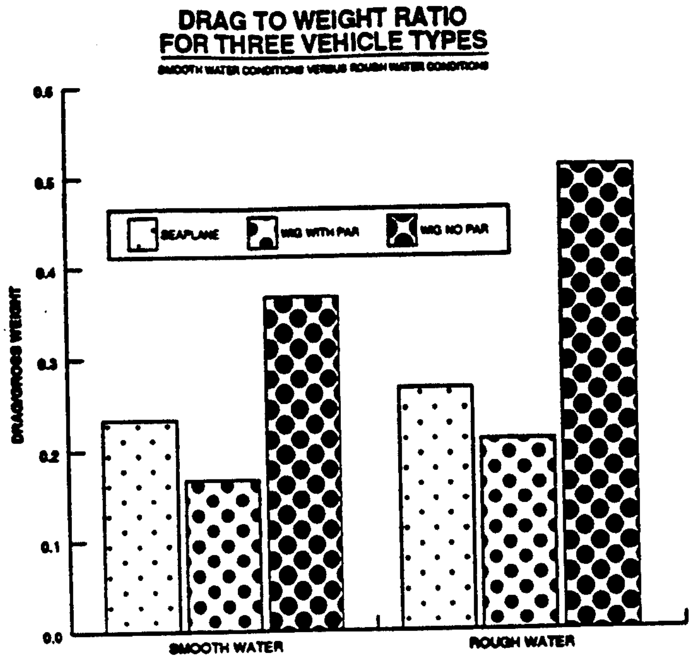


Figure 3-3 - Drag to Weight Ratio for Three Vehicle Types

When operating in rough water large spray sheets develop as the hull slams into oncoming waves. The large kinetic energy of the spray can damage wing flaps if they are extended and not designed with load alleviating devices. In the Russian LUN, the wing flaps are only partially deployed in this speed regime to avoid contact with spray.

At speeds somewhat below take-off, the hull continuously strikes the oncoming wave train. This wave impact establishes a high minimum structural weight for the vehicle.

Noise Abatement

Existing WIG vehicles make around 107 dB. The Federal Aviation Administration (FAA) does not allow noise to rise above 106 dB on three or more engines. In addition local municipalities have required DoD to reduce dB levels to 70 dB. A way to overcome this problem is to taxi the vehicle out to sea. Engines that can be used for taxi are discussed in the Section 3.1.2 (Propulsion).

Landing Technology

A "perfect" seaplane landing is one in which, after flare-out, the resultant velocity of the vehicle is nearly tangent to the free-water surface. In this instance, the craft settles into the water with minimal impact loads. Unfortunately, realistic seaplane flight path angles at water contact are not zero and the vehicle is at some positive trim angle relative to the water surface. Since wingships cruise in strong ground effect and land by slow deceleration their flight path angles are necessarily small.

There are few analytical or experimental data on wingship impact loads in a seaway and the Russians did not share their methodologies with the U.S. WTET. Seaplanes usually "bounce" off the initial wave and impact subsequent waves at steeper glide path angles and at different trim angles than the initial contact conditions. In fact, it has been found that the maximum impact loads in irregular head seas are developed in the subsequent run-out when there is little control of the seaplane-wave contact conditions. Empirical

methods for estimating the impact loads for seaplane landing in irregular seas have been developed based upon numerous model test results and are presented in the Wingship Investigation Final Report (Reference 4).

The impact acceleration increases linearly with beam. A hydroski has a smaller beam than the hull therefore it should reduce impact accelerations. This validates hydroski use on Russian ekranoplans.

3.1.1.3 Technologies and Deficiencies

The large power requirement to accelerate a wingship from rest to cruising speed is the single greatest impediment to the overall wingship utility. For this reason the Wingship Investigation issued a Broad Agency Announcement, pursuing a broad spectrum of takeoff technology concepts including those listed in Table 3-2. The government has awarded multiple contracts in an attempt to determine if there are any innovative technical approaches for reducing wingship takeoff power requirements. The approaches will focus on very large, heavy lift vehicles and are intended to provide a significant improvement over the state of the art. This section discusses concepts for drag reduction, PAR improvement, air injection and other innovative techniques under consideration.

Table 3-2 — Potential Technical Solutions

POTENTIAL TECHNICAL SOLUTIONS
Direct Underside Pressurization
Hydrodynamic Drag Reduction
Aerodynamic High Lift Devices
Shallow Water Drag Reduction
Vehicle Footprint (Cushion) Variation
LE & TE Flaps to Increase Wing Area
Peripheral Jets in Wing Endplates
Rechargeable Stored Energy Burst Thrust

Incremental Improvements in Hull Design

WIG drag value could be incrementally reduced with hull design improvements. Daniel Savitsky, extrapolating data from existing seaplane hulls, has calculated a drag to weight ratio of 0.15 for an improved seaplane hull weighing 2,000,000 lbs (Reference 4, Appendix "Wingship, Seaplane, and Landplane Capability Summary"). State of the art seaplane hulls have drag to weight ratios in the range of 0.20 to 0.23. The data presented in Figure 3-1 of this section was based on a seaplane with a drag to weight ratio of 0.23, a gross weight of approximately 44 lbs, a length to beam ratio of 6.5, and a Davidson loading coefficient, K_2, of 0.017.

Incremental Improvements in Power Augmented Ram (PAR)

PAR has been studied in the United States and used on vehicles in Russia. Recently observed Russian vehicles are not fully lifted off the water surface by PAR, making the WIGs a combination of a pure PAR vehicle and a pure seaplane hull. Some films show that the Caspian Sea Monster (in 1966) used PAR more aggressively. The use of PAR on Russian WIGs improved the drag to weight ratio relative to both seaplane

hulls and WIGs without PAR. Vehicle performance may be further improved by improving the application of PAR.

PAR has been studied in the United States and used on vehicles in Russia. Recent Russian vehicles have not been fully lifted off the water surface by PAR, making the WIG vehicles a combination of a pure PAR vehicle and a pure seaplane hull. Some films indicate that the Caspian Sea Monster used PAR more aggressively. The use of PAR on the Russian WIG vehicles improved the drag to weight ratio relative to both seaplane hulls and WIG vehicles without PAR. Vehicle performance may be further improved by improving the application of PAR.

PAR uses captured air pressure under the vehicle body and wings to augment the dynamic lift of the vehicle and the aerodynamic lift on the wings to achieve takeoff. On Russian vehicles PAR is provided by using forward mounted power systems.

We have estimated the theoretical potential performance from PAR and presented the results in Figures 3-4, 3-5 and 3-6. Increasing the length to beam ratio of the area effected by PAR reduces the thrust required for takeoff. In our analysis we increased the length to beam ratio from 0.2 to 10; this reduced the thrust to weight ratio at takeoff by 37% (from 0.27 to 0.17). The Russian Orlan vehicle has a PAR length to beam ratio of 0.32. The hull of the Orlan has a length to beam ratio of 11.53. Blowing air under the fuselage could reduce the thrust at takeoff.

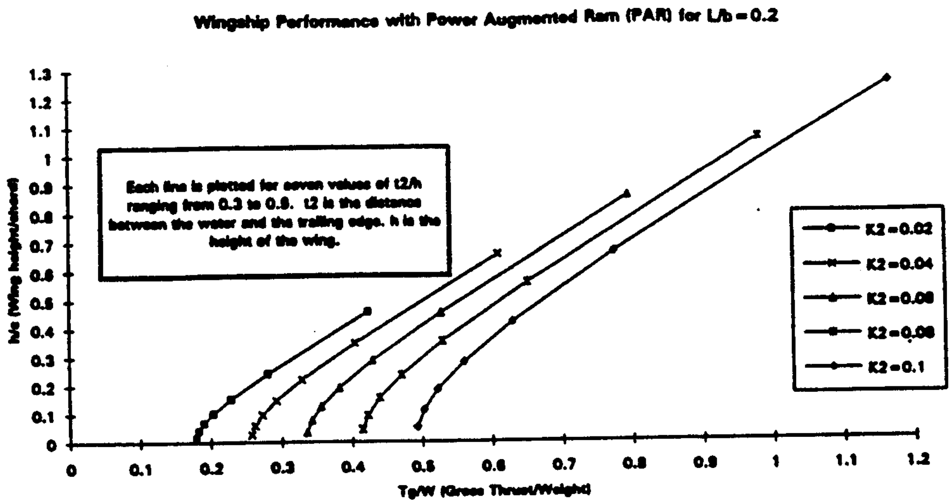


Figure 3-4 - Wingship Performance with Power Augmented Ram (PAR) for L/b = 0.2

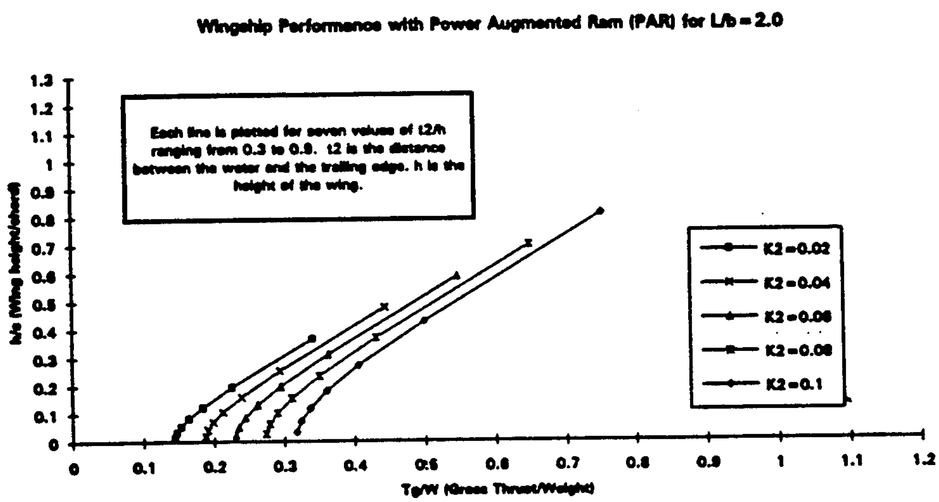


Figure 3-5 - Wingship Performance with Power Augmented Ram (PAR) for L/b = 2.0

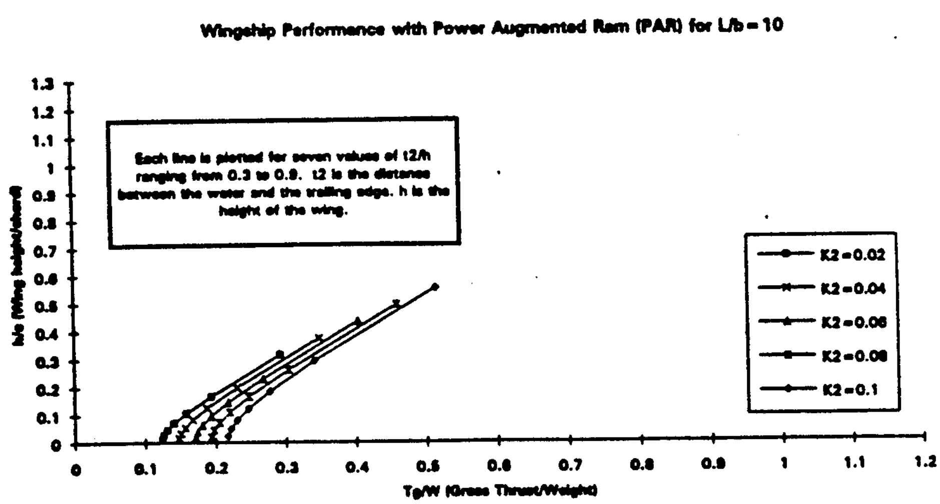


Figure 3-6 - Wingship Performance with Power Augmented Ram (PAR) for L/b = 10.0

The method used to develop these plots is presented in the appendix and is based on References 5, 6 and 7. The Russian Orlan vehicle typically has an h/c (wing height/wing cord) value of 0.1, a K_2=0.04 when fully loaded, and a length to beam ratio (L/b) of 0.32 for the area effected by PAR. In smooth seas the Orlan vehicle has a drag to weight ratio of approximately 0.17 (Reference 3, page WS63). In our theoretical analysis we assumed the vehicle had 0.1 gs of excess thrust at hump. For a vehicle similar to the Orlan (h/c= 0.1, K_2=0.04, L/b= 0.2) the thrust/weight ratio was 0.27, which is equal to a drag/weight ratio (D/W) of 0.17 (Figure 3-4). The theoretical calculation does not include the effects of skin friction and engine angle. Increasing the L/b ratio to 2.0 (Figure 3-5), reduced the thrust/weight ratio to 0.21 (D/W=0.11). Increasing the L/b ratio to 10 (Figure 3-6), reduced the thrust/weight ratio to 0.17 (D/W=0.07).

Noise Abatement

At present the method being considered to reduce noise at the beach is to move the vehicle away from the area — meaning taxi it out to sea and back, probably 5 to 10 nautical miles on takeoff and possibly even the same after landing. The main propulsion engines can not be used to taxi noise. Existing engine technologies can be applied to taxi the vehicle to the takeoff location, so that beach noise abatement requirements can be met. This is thoroughly discussed in Section 3.1.2 (Propulsion) and Appendix B.

Direct Underside Pressurization

Applying pressure to the WIG's underside results in a mode of operation during takeoff similar to a surface effect ship in that the high viscous drag associated with water contact is greatly reduced. The first successful wing-in-ground-effect vehicle was built by Toivo Kaario in Finland in 1935 (Reference 8, page 66). Kaario applied the direct underside pressurization approach and built a ram-wing snow sled. In the 1950s and 1960s Dr. Bertelson of Neponset, Illinois developed air cushion vehicles enabling him to reach his homebound patients (Reference 8, page 66). Presently the Air-Ride Company in Florida is attempting to commercialize the concept, using air cushions on boats. Recently Theodore W. Tanfield, Jr. was awarded a patent entitled "Near Surface Vehicle" (Reference 9). This is a small WIG which initially uses a diverted thrust air cushion to attain lift. It then uses airfoils to achieve lift at higher speeds. The vehicle has an aerodynamically shaped hull with rigid side walls and movable end flaps for forming an initial lift area. This concept, in principle, eliminates the thrust loss associated with the reversed flow at the PAR leading edge.

It may be possible to design a variable cushion area and variable length-to-beam. This could result in significant drag reduction at near hump speeds. Vehicles with low length-to-beam ratios have a low hump speed and very high drag at this speed. Wingships with high length-to-beam ratios have a higher hump speed and low drag at velocities around the hump speeds for low length-to-beam ratio wingships. The concept is to operate at a high length-to-beam ratio at low speeds, and low length-to-beam ratio at high speeds. When the low length-to-beam ratio hump speed is exceeded change the vehicle configuration to a low length-to-beam ratio which has a significantly lower drag at higher speeds than the high length-to-beam ratio vehicle configuration. This is discussed in more detail in the vehicle footprint section (below).

Direct underside pressurization is used in the development of wing-in-ground-effect vehicles. The challenge is to apply the concept to very large (400-ton and larger) WIGs.

Aerodynamic High Lift Devices

Another method to improve the wingship takeoff performance is use various active and passive means of increasing aerodynamic lift. Various methods such as enhancement of wing area, camber and circulation will be examined to increase the low speed lift without seriously degrading cruise performance. Passive aerodynamic methods include use of conventional flaps, slots, slates and other leading and trailing edge devices. Active methods include upper surface blowing, blown flaps, jet flaps, and cascade vortex shedders.

A.M.O. Smith reports that the maximum lift for any kind of airfoil is 4. The maximum lift near the ground is 4.49. (Reference 10, page 8) Ground effect increases the lift of real wings, but the maximum possible lift near the ground is substantially less than the maximum possible circulation lift in a free air stream.

If aerodynamic lift can be generated at lower speeds, less of the hull will be in the water, thereby reducing the hydrodynamic drag.

Vehicle Footprint

The idea behind changing the vehicle footprint is that wingships with low length-to-beam ratios have a low hump speed and experience very high drag at this speed, wingships with high length-to-beam ratios have a higher hump speed and relatively low drag at velocities around the hump speeds for low length-to-beam ratio wingships. This is shown in Figure 3-7 from Reference 8. The idea is to operate at a high length-to-beam ratio at low speeds, when the low length-to-beam ratio hump speed is exceeded change the vehicle configuration to a low length-to-beam ratio which has a significantly lower drag at higher speeds than the high length-to-beam ratio vehicle configuration. Designing a vehicle in which the length-to-beam ratio can be changed can result in a vehicle that can be operated in the lower drag regime for the full range of velocities experienced during takeoff.

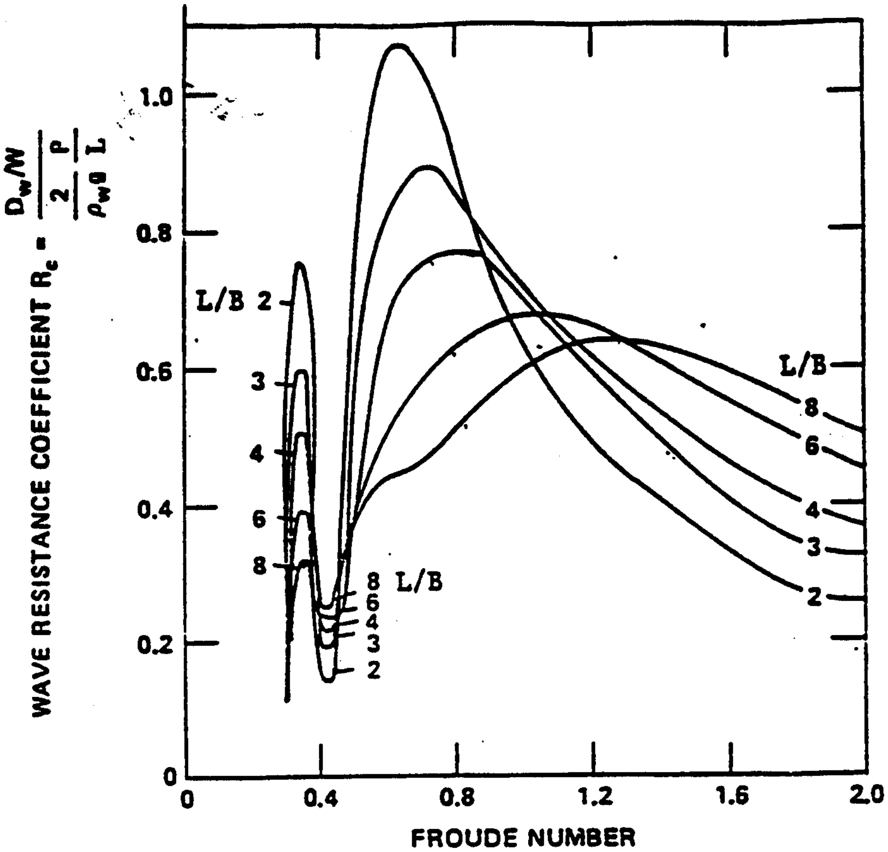


Figure 3-7 - Doctors' Wave Resistance Coefficient

Leading Edge and Trailing Edge Flaps to Increase Wing Area

This potential technical solution increases the wing area which, in accordance with the coefficient of lift equation, for a constant C_L would reduce the takeoff speed.(Reference 11, Chapter 8) Reducing the takeoff speed helps reduce the post-hump hydrodynamic drag and can potentially reduce loads on the vehicle structure allowing a lighter weight vehicle.

Another benefit of increasing the wing area is that it increases the L/b ratio of pressure patch. As discussed in the vehicle footprint section (above). this increases the hump drag velocity. The benefit of increasing the hump drag velocity is that the peak drag forces at high velocities are less than the peak drag forces at lower hump velocities. In addition with this type of vehicle, at the higher velocities it may be possible to reduce the drag at hump because of aerodynamic forces are more effective at lower speeds.

A problem with this approach is that it does require additional vehicle complexity and may increase the weight. Also, when the chord is increased, the aspect ratio is decreased (span/chord). This increases the induced drag.

Use of Peripheral Jets

Peripheral jets in the wing endplates may improve PAR efficiency by sealing the pressure under the wing and may augment vehicle thrust. Peripheral jets were used extensively on hovercraft in the "early days" as a means of providing the air cushion beneath the craft (Reference 12, page 155). The jets also provided an air curtain. The angle of the air curtain optimized cushion pressure and cushion area (Reference 12, page 38).

On some vehicles deflector vanes deflected air, providing propulsion (Reference 12, page 155,156). The application could be revisited to assess the feasibility on a wingship.

Momentary Thrust Augmentation During Takeoff

Developing ways to increase thrust momentarily during takeoff, such that the number of extra engines that must be carried during takeoff can be reduced is the idea here. One approach is to develop engines with thrust augmentation capability. This approach is described in the Section 3.1.2 (Propulsion). Other approaches include using rockets to assist takeoff or providing a system where excess energy during one phase of operation is converted to stored energy for use during takeoff. This concept is often evaluated in electric vehicle design.

The challenges with this concept are (1) the feasibility of developing a charge/discharge system integral to the vehicle and (2) the rocket concept reduces the wingship's flexibility; it can only takeoff from sites where rockets can be reloaded.

Hydrofoils and Hydroskis

Hydrofoils and hydroskis are underwater lifting surfaces which reduce the overall hydrodynamic drag by reducing the area in contact with the water. Preliminary analysis conducted as part of this study indicates that two reasonably sized retractable foils can potentially lift the wingship hull out of the water at speeds as low as 25 to 35 knots and reduce the hydrodynamic drag during takeoff for 400-ton size vehicles.

Hydrofoils and hydroskis can be used to absorb landing loads, reducing peak loads on the hull structure. The Russians use a hydroski in the vehicle's landing phase.

The challenges with this concept are cavitation problems, drag caused by the suspension systems, overall structural integrity, and weight penalties from the hydroski or hydrofoil and related mechanisms.

3.1.1.4 Technology Development Program

Wing-in-ground-effect vehicles do takeoff and for some missions the existing inefficient operation at cruise (due to excess thrust) is acceptable. For other missions takeoff technology must be developed.

The technology development for landing is discussed in Section 3.1.3 (Structures).

Both the Russians and WTET agree that the landing process develops critical structural design loads and should be examined in much greater detail. These studies should be conducted by model tests in controlled and repeatable seastates. Unfortunately, the wave maker at the Central Aero Hydrodynamic Inst. (TsAGI) towing tank isn't capable. Studies of the landing behavior in waves in suitable towing tank facilities are highly recommended.

The Takeoff Technology Roadmap (Figure 3-8) assumes that takeoff technologies need development to enable the mission. The roadmap considers the development of technologies for all size vehicles (400-ton to 5,000-ton), initially focusing on the 400-ton size vehicle. We estimate that all work in preparation for the U.S. 400-ton vehicle Preliminary Design Review (PDR) will cost $23 million. We estimate an additional $10 million to integrate the selected design into the final 400-ton vehicle.

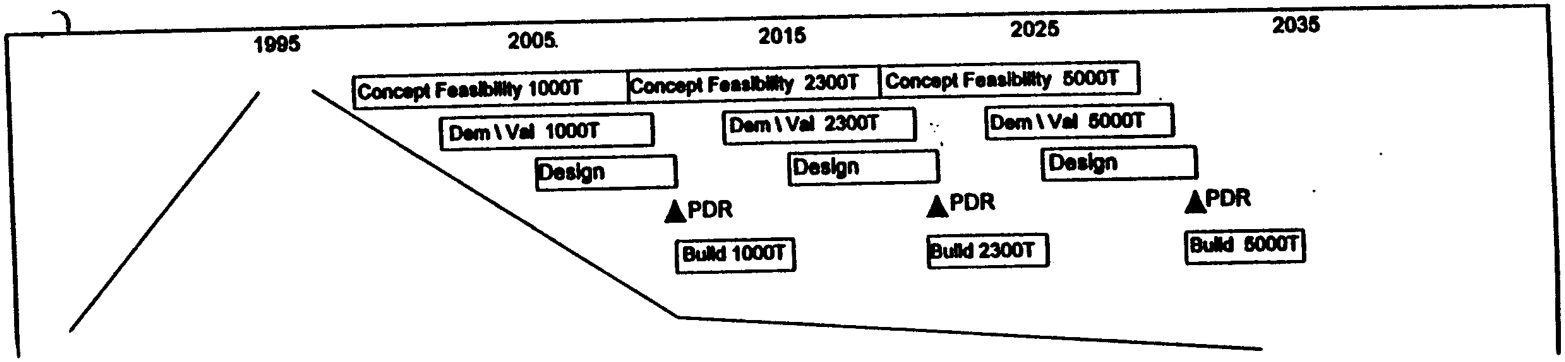
A solution to the takeoff problem is not obvious. The wingship takeoff maneuver is controlled by extremely complicated unsteady aerodynamic-hydrodynamic interactions. Formulating a numerical model

of this complex interaction is difficult and the results from such models are questionable without sufficient validation data. The roadmap includes analysis supported by experimental data. Experimental work will be conducted using models varying from small scale size to full scale.

The first step is to focus studies on a 400-ton vehicle. As we learn more about the 400-ton vehicle, it will be easier to determine the feasibility of the 1,000-ton vehicle. From the 1,000-ton vehicle work it will be possible to determine the feasibility of the 2,300-ton vehicle and then the 5,000-ton vehicle. At some point it may be decided that either a vehicle size is not feasible, or that we have determined a larger size is very useful and feasible and that efforts should be focused on that size.

The Takeoff Technology Roadmap charts the exploration of takeoff technology for wingships of all sizes. We have specified four basic phases for the development of each vehicle size: Concept Feasibility, Demonstration/Validation, Design and Build. We begin the exploration by focusing on a 400-ton vehicle and explain our proposed approach in some detail. There is much we do not understand and experimental work is critical in determining the concept feasibility. A major factor is understanding the validity of scale-up factors. As scale-up of takeoff technology becomes better understood, the feasibility of larger vehicles can be better assessed.

Takeoff Technology Roadmap



Activity Name	Duration	Cost
400 Ton Takeoff System		
Concept Feasibility	20 months	$1.9M
Technology Feasibility Studies (BAA)	6 months	$500K
Assess Concepts / Select	2 months	$250K
Develop Test Program / Model	6 months	$500K
Conduct Model Test / Analyze	4 months	$500K
Select Technologies	2 months	$150K
Demonstration / Validation	42 months	$16.5M
Develop LUN Test Program	18 months	$1.5M
Design System for LUN	18 months	$ 3M
Fabricate / Install Takeoff Systems (LUN)	18 months	$ 6M
Demonstrate Takeoff Technology (LUN)	18 months	$ 6M
Design	24 months	$4.6M
Design Takeoff Systems	18 months	$ 4M
Select Takeoff Systems	6 months	$500K
Conduct Preliminary Design Review (PDR)	2 months	$100K
Build / Integrate Takeoff System	72 months	$10M
400 Ton Takeoff System Total		$33M

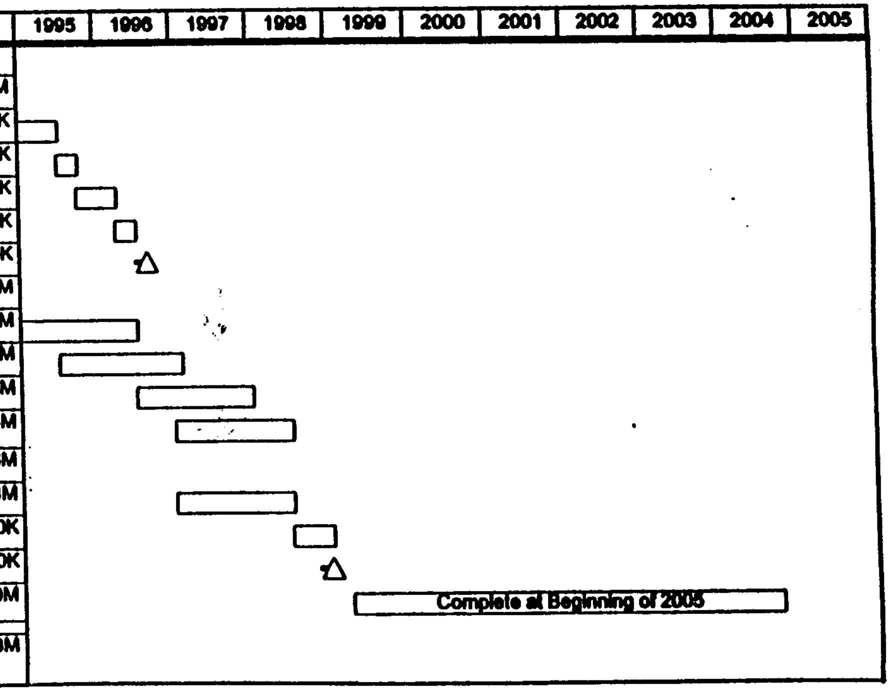


Figure 3-8 - Takeoff Technology Roadmap

Takeoff Technology Roadmap Description

The roadmap includes four phases for each vehicle development: (1) Concept Feasibility, (2) Demonstration/Validation, (3) Design and (4) Build. There are four vehicle sizes being developed: 400-ton, 1,000-ton, 2,300-ton and 5,000-ton. We assume that each vehicle takes 10 years to develop and build and that it will take 40 years to build a 5,000-ton size wingship. The following description focuses on the tasks in each phase in developing a 400-ton vehicle. The development of other vehicle sizes will be similar if it is determined that the size is feasible and has a purpose.

Concept Feasibility

The Concept Feasibility Phase consists of five tasks: (1) Technology Feasibility Studies, (2) Assess Concepts/Select, (3) Develop Test Program/Model, (4) Conduct Model Test/Analyze and (5) Select Technologies for Specific Vehicle Size.

Technology Feasibility Studies

The preliminary work for this task began when the Advanced Research Projects Agency (ARPA) issued a Broad Agency Announcement requesting proposals. On the roadmap this task begins when ARPA awards the contracts. We have assumed October 1, 1994. In this task multiple programs are conducted to develop and/or apply advanced technologies for reducing the large power requirement to accelerate WIG vehicles from rest to cruising speed. This is a six-month task and will cost $500,000.

Assess Concepts and Select

The government will assess recommended concepts as a result of the Broad Agency Announcement (BAA) process. Considered factors include improvement to takeoff performance, impact on cruise performance, vehicle takeoff weight, payload weight, operational performance and cost. In this task the government will select the "most attractive" concepts for further study. This is a two-month task and cost $250,000.

Develop Test Program and Scale Model

The purpose of the task is to design scaled model experiments to verify feasibility studies. The technical team needs to identify facilities where testing can be conducted, design a test program to investigate scaled model issues, and build and/or modify existing models for experimental work. This is a six-month task and cost $500,000.

Conduct Model Tests and Analyze Results

The purpose of this task is to conduct scaled model experiments to collect data on takeoff concepts, analyze data and verify performance improvements with experimental results. This is a four-month task and cost $500,000.

Select Technologies

The purpose of this task is to select takeoff technologies for further development in the Demonstration/Validation Phase for the 400-ton vehicle. The takeoff technology team will coordinate with propulsion and structures in selecting takeoff technologies and in identifying technical requirements for the three technology areas. This is a two-month task and cost $150,000.

Demonstration/Validation

The Demonstration/Validation Phase consists of four tasks: Develop LUN Takeoff Test Program, Design Takeoff Systems for LUN, Fabricate and Install Takeoff Systems and Demonstrate Takeoff Technologies on LUN. This is a four-year phase beginning at the same time as the Concept Feasibility Phase and culminating at the 400-ton vehicle PDR. This is the full scale testing portion of the program. As concepts are analyzed and tested in the Concept Feasibility Phase, data will be used to determine testing requirements for the LUN and to determine the feasibility of testing concepts on the LUN. There are concepts that may be promising, but difficult to test on the LUN. This will be determined in the design task and the information will flow back to the Concept Feasibility Phase. Data obtained in this phase will be used to determine the effectiveness of scale-up factors.

Develop LUN Takeoff Technologies Test Program

Determine the parameters to be evaluated (velocity, vehicle loads, acceleration, effect of seastate and etc.) and identify data collection methods. Design a test matrix and coordinate with small scale modeling experiments being conducted in the Concept Feasibility Phase. Numerous test matrices will be developed to evaluate the numerous takeoff technology concepts, and modified as the concepts become more developed. This task is estimated to be 18 months long and cost $1.5 million.

Design Takeoff Systems for LUN

Begin design of promising takeoff technologies. Determine if technology can be tested on the LUN. For promising concepts which can be tested on the LUN, do the design work needed to fabricate and install the technology on the LUN. This task is estimated to be 18 months long and cost $3 million.

Fabricate and Install Takeoff Systems

Fabricate equipment for installation on the LUN. Install systems of the LUN. This task is estimated to be 18 months long and cost $6 million.

Demonstrate Takeoff Technologies on LUN

This is the full scale evaluation of selected takeoff technologies. Analyze results, modify testing as required, verify scaling laws for 400 ton vehicle. This task is estimated to be 18 months long and cost $6M.

Design

The Design Phase consists of three tasks: Design the Takeoff Systems for the U.S. 400-ton vehicle, Select the Takeoff System for the U.S. 400-ton vehicle, and Conduct the U.S. 400-ton vehicle Preliminary Design Review (PDR).

Design

Design takeoff systems for the U.S. 400-ton vehicle, using results from the LUN testing and from the small scale testing. This task will be conducted in parallel with the LUN testing. It is estimated to be 18 months long and cost $4 million.

Select Takeoff Systems for 400 ton Vehicle

Based on the results of the model tests, LUN tests, and design efforts from FY 95 through FY 98, select and integrate takeoff systems into the U.S. 400-ton vehicle design. This task is estimated to be 6 months long and cost $500,000.

Conduct Preliminary Design Review (PDR) of U.S. 400-ton Vehicle

This is a major milestone and occurs four years after program initiation. The design of all selected WIG technologies is reviewed. This milestone marks the end of the research work for a 400-ton vehicle and the beginning of the vehicle build process. This is estimated to require two months to gather and prepare information for the PDR. The total cost for takeoff technologies is estimated to be $100,000.

Build the U.S. 400-ton Vehicle

This is estimated to be a five-year process. The takeoff technology system cost depends on the final one selected. From design, fabrication, build and integrate we estimate the takeoff system will be around $10 million.

3.1.2 Unique Propulsion Requirements for Large Wingships

This is a development plan for unique propulsion technologies to power large wing-in-ground-effect (WIG) vehicles ranging from 400 to 5,000 tons. The specific plan to flight test 400-ton WIG by 2005. The intent is to give the U.S. a unique advantage over the rest of the world by developing technology that would reduce engine size and costs by half compared to the rest of the world, including the Russians.

The principal propulsion technology offered in this section is a fan duct augmentor. The augmentor is worth a 40% reduction in "dry" engine size, weight and maintenance costs in service. If all propulsion and propulsion related development tasks work as hoped, our WIGs could use about 60% less on the wing thrust than any other nation, including the Russians who have pursued WIG development for nearly 30 years.

The plan is comprehensive — going from Concept Formulation (6.2) to Demonstration/Validation of critical technologies (6.3) and then Full Scale Engineering Development (6.4). Ten years is required, in three well-managed phases suitable to the normal military development cycle for acquisition. The costs in each level are $10 million, $38 million and $243 million for a total of $291 million.

The plan is built around three keystones — (1) competitive engine selection and sizing via extensive testing and evaluation at Arnold Engineering and Development Center (AEDC) under a simulated sea-salt-in-air environment, (2) keeping both technical and development milestones coordinated with major vehicle developments that will have a strong impact upon engine sizing and (3) well founded research development, test and evaluation (RDT&E) to ensure either no toxic problems from combustion in the presence of sea salts or a positive mitigation throughout development if problems are encountered. The later environmental aspects of the plan are highly integrated with the development and test of engine hardware at all three development levels.

3.1.2.1 Assumptions and Requirements

The following sections develop the large wingship technology roadmap for propulsion systems. The planning objective is to emphasize the roadmap for critical technologies at escalating levels of development, from exploratory (6.2) to engineering development (6.4), as part of an overall and integrated propulsion plan.

Major assumptions are:

The planning focuses on vehicles that demonstrate advanced capability by using U.S. technology in a development program supported by American interests — predominantly military and most likely Navy Sea Systems Command (NAVSEA) managed.

While some U.S. component technology capabilities in engines are considered extensive and far superior to the Russians, our knowledge of how to best use them in WIGs is limited. The assumption is that American technology in WIG components — structures, actuators, controls, navigation, sensors, propulsion systems and etc. is probably the world's best and can be used to master any task, providing the task's requirements can be defined.

U.S. large WIG experience is limited to studies and what we gleaned from the Russians. Using Russian experience and equipment, at least until our requirements are based on our own experience, is in our own

best interests. In August 1993 the WTET examined a four-engined LUN under construction in Russia. The shell was assembled but interior work wasn't in progress nor were engines installed. In order to gain needed experience, the U.S. will acquire such a shell and finish it off with our equipment, including engines and related items.

U.S. mission analysis suggests that WIGs even up to 5,000 tons might be useful. Progressing to that size from the present Russian size of about 400 tons may best be done in growth steps of 2 to 2.5 multiples. This, and about 10 years or so between generations, produces the following schedule:

WIG For U.S. Test and Evaluation		
Generation	**Size**	**First Flight Date**
1st	400 tons	2000-2005
2nd	1,000 tons	2010-2015
3rd	2,300 tons	2020-2025
4th	5,000 tons	2030-2035

Because vehicles of these sizes are sufficiently large and expensive, each one that is built needs to have lasting utility. It is not practical to discard or put them in a museum following a test and evaluation program as is common with experimental aircraft. Every vehicle built — even though the primary goal may be technology demonstrations and assessment — may be used for 10 to 30 years. In order to ensure that the vehicle is useful, we must remain aware of our operational requirements.

WIG thrust/weight (T/W) ratio at takeoff is similar to large commercial aircraft T/W ratio at takeoff — on the order of 0.25. (The minimum for takeoff with PAR for WIGs is 0.25.) However, at sea level, WIG engines do not experience the altitude decay in thrust at cruise that aircraft powerplants do. Consequently, WIG powerplants suffer from considerably excessive thrust at cruise putting them on "the backside of the Specific Fuel Consumption (SFC) versus thrust curve," where SFC is high and increases with reductions in thrust (or drag).

At present, the Russian LUN cruises by shutting down several engines and letting them windmill. Ways to reduce windmill drag might be welcomed, such as a variable pitch fan feathered upon shutdown. Our proposed approach is to avoid or reduce windmill drag by developing fan duct augmentation. The augmentor is worth a 40% reduction in "dry" engine size, weight and maintenance costs in service.

When the vehicle approaches 2,500 tons, the number of engines per WIG might exceed eight. If the number of engines grows much higher, WIG availability suffers because the nearly constant need to perform post-flight propulsion system maintenance. A 20-engined vehicle is expected to have 2.5 times the post-flight maintenance effort of an eight-engined vehicle. For a very large WIG of 5,000 tons, the preferred approach is to preserve availability would be to use eight large thrust class engines — 300,000 lbs dry/400,000 lbs wet.

Propulsion should be sized to permit safe takeoff despite the loss of one out of every four engines. (This is a present civil requirement.) It is immaterial where this additional thrust comes from on the vehicle as long

as it is adequate to keep the T/W ratio no less than 0.25 and it has no objectionable refueling or critical characteristics like rocket assisted takeoff (RATO) or jet assisted takeoff (JATO).

The thrust vector requires approximately 20° to 25° of downward deflection to provide underwing blowing for PAR. Thrust vectoring is only required for PAR. PAR is a powerful means of minimizing T/W ratio if properly applied. PAR can drop the T/W for takeoff down to 0.25 which is 40% to 60% less than for seaplanes at about 0.35 to 0.40.

If range is short, 1,500 miles or so, the vehicle could be overthrusted (T/W = 0.35+) for takeoff and PAR is not required. Overthrusting would be less efficient but not all mission applications require full optimization. Eliminating PAR would likely eliminate both thrust vectoring and the hot fuel leak problem and might admit to more augmentation.

Since takeoff sizes the engines, the impact of the ARPA 1994 Broad Agency Announcement for takeoff technologies and the extent of assistance on takeoff from PAR must be accommodated when sizing the engines.

<u>Noise abatement requirements</u>

The noise from one large 50-ton class turbofan, even with sound treatments in the fan, exhaust and nacelle might still be 101 or so dB, plus augmentor noise. Doubling the sound source number adds 3 dB. Noise limitations imposed upon DoD operations are controlled by local municipalities and not the federal government. Compared to the Russian experience, special operational requirements to abate noise are very uniquely American. Existing DoD environmental regulations require the developing activity to mitigate such problems throughout the system life cycle, starting early in the development cycle.

One approach to reduce both noise and fuel requirements during an extensive taxi is using internally mounted turboprop engines to drive a set of screws or jet pumps in the water. This "taxi" arrangement may be capable of providing enough thrust during takeoff to effectively compensate for one engine out on takeoff, thereby reducing the on-wing propulsion needs, weight, drag and cost by 25%. Such a "taxi assisted takeoff" is called TATO.

Table 3-3 for engine sizing provides the vehicle sizes permitted for a range of individual engine thrust levels and the number of engines. The table assumes a T/W ratio of no less than 0.25 and allows for engine failure on takeoff. The engines are assumed to have 40% overall thrust augmentation via a fan duct augmentor, and each has been derated 5% in overall thrust level to accommodate the build up of salt deposits in the gas path during a single mission. Basic engine size is stated in terms of its aircraft rating without augmentation or derating. Some examples as applied to the preceding WIG growth steps shown previously are:

- 400-ton WIG - (no TATO) would need four high bypass turbofan engines with an aircraft rating of 50,000 lbs, each of engine would need to produce 66,500 lbs of thrust after 40% augmentation despite a 5% thrust derate for in-flight salt. For six engines, their dry rating on aircraft would be 30,000 lbs For eight, the augmented value with 5% derate would be about 25,000 lbs.
- 1000-ton WIG - (no TATO) several sizes could be made to apply depending upon what was most desirable at the time, i.e. six aircraft engines rated at 75,000 lbs thrust, eight engines rated at 65,000 lbs or 10 engines rated at 50,000 lbs.

- 2,300-ton WIG - (no TATO) the various candidates would be greatly reduced because the large vehicle weight would require 10 engines and they would be rated at about 95,000 to 100,000 lbs thrust.
- 5000-ton WIG class (10,000,000 lbs) - (No TATO) engines in the 300,000 lbs dry (400,000 lbs wet) thrust class are preferred - or it could use 22 engines rated at 100,000 lbs dry, 140,000 lbs wet. The success of large WIGs would justify the development requirement for some very large engines. Engine development should lead first flight by the time of a new engine generation — 10 years.

To enhance the integration of WIGs with conventional Naval or merchant ships, plus harbor docking facilities, WIG propulsion units should be converted during engineering development to ship fuels — such as diesel fuel marine (DFM)/Navy distillate (ND).

TABLE 3-3 - WIG TOGW/Engine Sizing Requirements

WIG TOGW/ENGINE SIZING REQUIREMENTS (WITH NO ASSIST FROM TAXI ENGINES)

	A/C Eng Dry Max TO Thrust, Klb	WIG Max TO Thrust with 5% Derate + 40% Aug	WIG TOGW with Engines Out, KLb				
			Engines Installed	4	6	8	10
			Engines Out	1	1	2	2
Multipliers	(1.0)	(1.33)		(12)	(20)	(24)	(32)
	20	26.6		319	532	638	851
	30	39.9		479	798	958	1277
	40	53.2		638	1064	1277	1702
	50	66.5		798	1330	1596	2128
	60	79.8		958	1596	1915	2554
	70	93.1		1117	1862	2234	2979
	80	106.4		1277	2128	2554	3405
	90	119.7		1436	2394	2873	3830
	100	133.0		1596	2660	3192	4256
THE FOLLOWING REPRESENT VERY LARGE ENGINES NOT YET DEVELOPED							
	150	199.5		2394	3990	4790	6390
	200	266.0		3190	5320	6390	8500
	250	333.0		4000	6660	8000	10750
	300	399.0		4790	7980	9600	12800

Assumed Daily/Mission And Maintenance Cycle

In order to help define propulsion requirements the daily mission and major maintenance cycle was examined from a propulsion viewpoint. This analysis is presented below.

Base of operations — The WIG operates from a protected harbor or WIG tender although it is to be capable of discharging cargo at a beachhead. Following today's Naval aircraft engine practice, even such

short engine operating time at or near beaches will add erosion to the engine airfoil coating corrosion requirement.

Propulsion Aspects of a Mission Cycle

1. The WIG is loaded and then exits the noise abatement area by motoring at 10 to 20 knots, five to 10 miles out to sea on one to three internal T56s driving screws or a jet pump.
2. The main propulsion engines are started from an onboard compressed air generation and distribution system.
3. PAR takeoff (without TATO) is made over a period of up to two minutes and begins with rotating the thrust vector under the wing and activating the afterburner. (If TATO is used, it and the main engines are advanced to maximum power for a quick takeoff run.) During takeoff, large quantities of "green water" splashing into the engine inlets on the canards is a problem. Severe flameout-like power losses could occur if the water cannot be separated from the air stream. Water/air separation with very low pressure recovery losses at cruise is needed. A separator might effectively extract fine liquid water particles (sea salt in air) during cruise, but the main requirement is takeoff.
4. After achieving wing-borne flight, the duct burners are turned off and the thrust vector rotated up to cruise position. The vehicle accelerates under dry power. At least one TATO engine is left running to handle accessory drives for aircraft power. Engine power is reduced at cruise. If an adequate thrust turndown ratio cannot be achieved without large increases in SFC, then several engines need to be shutdown.
5. Landing will be accomplished by dropping flaps and extending a wide hydroski near the vehicle center of gravity to keep major loads from the plating of the hull. The windmilling engines may have to be restarted. Thrust augmentation should not be required for landing.
6. All the main engines are shut down, TATO is re-engaged to the propeller shafts/jet pumps via the gearbox and the WIG is taxied back to the dock, harbor or tender. TATO also provides the auxiliary power source and an air supply to motor engines, run instruments and navigation equipment, and power controls.
7. Upon reaching the docking facility engines are washed over the next hour as the WIG is unloaded, using the onboard auxiliary power unit to power the all engine starters simultaneously and continuously at less than starting rpm. Most important variables for this are coarsely estimated today.

3.1.2.2 Today's State of the Art, Preferred Technologies, Deficiencies

The following describes what propulsion technologies are available today, what new technologies are needed and what deficiencies stand in the way.

Engines Available

Existing large commercial high bypass turbofans are capable of delivering 52,000 to 53,000 lbs dry thrust each, without using augmentors, and four engines might be adequate for 400-ton WIGs. (Included are engine models from the CF6-80 and the PW4000 series currently used on A300, 310, 330, B747, 767 and 777's. The CF6 series was introduced around 1970, and the PW4000 series came out about 1985.) Versions of these engines, with the dry commercial maximum rating, are in current commercial service and are listed as:

Candidates for 400-ton WIG with four engines	
Engines	Pounds of Dry Commercial Thrust
CF6-80C2A2	52,460
CF6-80C2B2	51,570
CF6-80C2B2F	51.650
PW 4152	51,000
PW 4052	51,200
JT9D-59A,7QA,7Q	52,000
JT9D-7R4E, El	49,000
JT9D-7R4G2	53,500

Each engine needs (5%) downrating for salt buildup and 40% augmentation for an approximate takeoff thrust value of about 66,500 lbs. If the TATO concept is used, engines would need be sized down from the 66,500 lbs to 50,000 lbs wet/35,700 dry. At present, the only U.S. high bypass turbofans in this size range are older versions of the JT9D at 43,000 lbs or CF6 at 52,500 lbs that need substantial downratings, and the more recent PW 2037 in the PWA 2000 series. The PW2037, however, is rated at 38,250 lbs (B757-200) and the PW 2237 is rated the same and is for the Ilyushin IL-96M, scheduled for certification in 1995. (See the appendix for information on the PW 2000 series.) The PW 2037 has an 85" diameter one-stage fan (unmixed discharge) with IGVs. This engine has international participation — PW 71%, MTU 21%, FIAT 4% and Swedish Volvo at 4%. The PW 2000 series is similar enough to the PW 4000 series or the GE90 that augmentor information ought to transfer to the larger and newer engine size. This should be assessed for application to the TATO concept.

For WIGs of 1,000 or more tons, the latest high bypass ratio commercial turbofans (PWA 4084, GE90) in the 85,000 to 100,000 lbs dry thrust class are good candidates. They will be introduced into commercial service at 75,000 to 77,000 lbs in 1995. Table 3-3 shows that a six-engined 1,000-ton, case becomes viable when the dry rating reaches 76,000 lbs. At the full 100,000 lbs of dry thrust, eight engines with 40% augmentation would be the basis for a 1,600-ton vehicle and 10 engines could power 2,100 tons.

The high bypass commercial turbofans are candidate engines not because of their particular cycle specifics but because they will shortly be available and they are large. The characteristics of these engines plus a few Russian ones that might be applicable are in the "Available Engine Characteristics" part of the Appendix B (Propulsion).

Any engine selected for WIGs will require "marinization", a NAVSEA term. Marinization means using cold and hot section coatings and substituting materials for those more resistant to corrosion. Marinization would be no riskier than normal engineering development.

The unranked list of preferred and unique WIG propulsion technologies desired for any of these engines, regardless of size, model or availability includes (candidate engines are presently deficient in these capabilities):

- 40% fan duct thrust augmentor
- marinization of engine installation for WIG operations
- low pressure loss "green water"/inlet air separators
  - erosion and corrosion coatings for fan and compressor
  - material substitutions for salt environment
  - downratings for salt deposition in-flight
  - water wash provisions
- one-hour continuous duty low rpm starter system
- in-situ water wash probes
- no manual connect/disconnects for washing
- salt spray deposition engine signature definition
- minimum water wash and emergency sea water wash procedures
- lower operating line in the high spool compressor
- drop the turbine inlet temperature to accommodate sea salt deposits on both compressor airfoils and the turbine vane throats that are likely to occur during a single mission.
- windmill drag reduction via "feather" capability in the fan
- Ensure bearing will tolerate long windmill periods
- Ensure that no extreme health hazards are created by the combustion of salt water with diesel marine or jet fuels during any anticipated mode of gas turbine operation, including starting with very wet internal engine parts and shut down.

If there wasn't a need to go beyond a 400-ton WIG or if PAR and thrust vectoring was not required (as with a relatively short range vehicle) then there might be a WIG market for existing mixed flow, augmented turbofans now in the U.S. military inventory. Table 3-3 (assumed the use of PAR — for no PAR, multiply all engine sizes by 1.4 to 1.6) showed that such candidates would require an augmented thrust value (prior to the 5% derating) of about 26,500 lbs for 10 engines, 35,000 lbs for eight engines or 42,000 lbs for six engines. Engines that could provide those thrust levels today are the F110-GE-129 (29,000 lbs wet and 17,000 dry) and the PW F100-PW-229 (29,000 wet and 17,800 lbs dry) for the 10-engined case. For the eight-engined case, the PW F119 at 35,000 lbs wet (21,000 dry) from the USAF F22A also has a 20° nozzle deflection capability, which might not be an asset unless PAR was needed. The three spool low bypass mixed flow Russian SAMARA NK-321, from their Blackjack bomber, which is not U.S. technology, would provide needed thrust in the 42,000 lbs class at 55,077 lbs wet/30,843 lbs dry. Another advantage to these military engines is that their augmentation ratio is quite high, 60% to 70%, meaning that the thrust rollback needed for good cruise is 1.6 to 1.7 which is better than the 1.4 selected for the fan duct heater discharging at 800° F. Unless a mission surfaces that does not need PAR but does need an augmentor (with discharge gas temperatures prior to external mixing of 3300° F to 3450° F.) or a mounting scheme is selected that does not threaten fuel tanks, the use of high temperature augmentation via new, large, mixed flow, military turbofans is less desirable choice and will not be the major propulsion planning

path here. The plan will nonetheless accommodate "no PAR" and a thrust/weight ratio of 0.35+ since the plan must allow for uncertainty and not prejudge critical choices.

Inlet air/water separators for splash protection

One Russian WIG, with nose mounted lift engines, is said to have used a very complex set of anti-iced, inlet mounted "venetian blinds" to accomplish inlet air/water separation, since these engines did not run at cruise. The LUN in construction uses an engine inlet with a center-mounted spire resembling a Greek Orthodox church spire or "onion." The shape is evidently intended to use the high inertia of the ingested water to separate water and air streams. Separation would occur as the flow moves around the body of the "onion," the air staying with the contour but the water continuing axially with much of it hitting the outer wall. Similar shapes have been investigated via both engine and flight tests in the U.S. to eliminate rpm losses to sub-idle values on both turbojets and medium to high bypass turbofans during severe in-flight rain ingestion. The problem usually appears like a flameout but is simply a large speed drop caused by the fuel control's inability to deliver adequate enrichment during core water ingestion. Solutions are frequently elusive. Development of a spire solution might be no more uncertain than engineering development.

Obtaining low SFC at cruise - (See assumptions for discussion of SFC problem.)

Three possible cycle solutions are visible:

1. Use an Advanced Ducted Propeller (ADP) which may contain a variable blade angle feature. By 2000, ADP should be a state-of-the-art capability and would be available if needed. We made a preliminary analysis to investigate the effect of high bypass ratios on SFC. The computer SFC decreases about 13% as the bypass ratio increases from 5 to 15. The ADP is said to be under evaluation by Pratt and Whitney Aircraft (PWA) for use in commercial high bypass engines over 100,000 lbs thrust after the year 2000. These future engines would also the ability to make reverse thrust by varying fan blade angle. For WIGs the ADP could be used as a means to "feather" the fan and eliminate most of the windmill drag at cruise. While WIGs do not need reverse thrust, the ability for variable thrust gearing to greatly minimize windmill drag might make the added weight of 1,000 lbs or so per engine worthwhile. Windmill rpm of the core is normally very low even when the fan can rotate. If the fan is stopped, core speed might be even lower. An assessment should be made of the effect of very low axial loads upon skidding of ball thrust bearings in the high rotor at windmill. If skidding exists, ball fatigue and very short bearing life will result. Whether the fan is feathered or not, restarting the core will likely require using starter, particularly at less than 0.6 to 0.7 Mach. The development of such an ADP would be expected to come from commercial sources with a 6.4 adaptation to program WIG feathering.
2. Relieve the main propulsion engines on the wing of the responsibility of providing 25% extra available thrust (a FAA requirement) to allow safe takeoff despite the loss of one engine. This might be done by using of several 5,000 SHP class inboard shaft drive gas turbines driving screws or jet pumps. These engines will likely be needed for 5- to 20-mile taxi runs to avoid making excessive noise at beaches and harbors. Using these same engines for takeoff assist would be a novel, workable and practical means of reducing thrust on the wing. (See TATO at the end of the Noise Abatement in Assumptions in this section [Propulsion} and in Appendix B.) TATO is seen as a good 6.2 acquisition program candidate.
3. The third option might be applying variable cycle engine (VCE) features including variable entry area high pressure (HP) and low pressure (LP) turbines and variable compressor inlet guide vanes.

However, these features have not been explored on a VCE deck. Although, the Naval Air Warfare Center/Aviation Division/Trenton still has the analytical capability, as verified 6 May 94, which will move to Patuxent River, Maryland in 1995. While a thrust turndown of 3:1 and retention of near minimum SFC may be optimistic, this should be verified or denied on a simulation. Cost and complexity need to be dealt with. The U.S. built and ran advanced VCEs since the late 1970s, using advanced components throughout from the 6.3 funded Advance Turbine Engine Gas Generator Program (ATEGG) and the Integrated High Performance Turbine Engine Technology Program (IHPTET), with participation from DoD, NASA and corporate internal research and development (IRAD). However, that none of the engines built and tested were unmixed flow turbofans. This third option is clearly a 6.2 acquisition program

Augmentors

In trying to minimize the SFC problem at cruise via cycle selection, a kindred approach is the use of an augmentor for a 40% thrust boost on takeoff. Although both the U.S. and Russia have developed many augmentors for both turbojets and mixed flow turbofans, no one has developed one for a fan duct on a non-mixed-flow engine, particularly one with a low pressure ratio fan and very high airflow. An assessment of how difficult it would be to build a fan duct heater for 40% thrust augmentation with good probability of successful operation must be done before such a device could be seen as exploratory or engineering development. Factors that are difficult for combustion include the low fan discharge temperature and pressure — 143° F and 1.6 atmospheres.

High temperature environment for wing/fuel tanks.

This is likely needed for propulsion if an augmentor and PAR is used with vectored thrust. However, since it is a vehicle item and not propulsion, whatever concepts emerge, look to Section 3.1.3 (Structures). (See the Appendix B, Propulsion .)

Vectored thrust

Presently the Russian LUN engines are mixed flow turbofans. The exhaust stream is deflected for PAR by using a half-round piece of ductwork which pivots downward in the nozzle discharge plane during PAR. This is an extremely simple system which probably required little development, but may be inefficient.

For mixed flow turbofan streams on V/STOL aircraft, the Russians have round, deflected thrust, nozzles using segmented pipes capable of 100° of turning. The U.S. has developed both pitch and yaw mode, deflected thrust, high temperature, round nozzles which are functional to +/- 20°, but they are heavy, complicated and expensive. The AV8 Harrier is the only aircraft utilizing deflected thrust on a non-mixed-flow turbofan and does so via bifurcated ducts inside the aircraft on both the fan and core streams feeding four round, rotating nozzles. Tilting the WIG canards with all main engines mounted on them is partially analogous in V/STOL to tilt-nacelle vehicles, such as the V-22. It is directly analogous to tilt-wing V/STOL aircraft. Rotating the canard on a WIG might be done. See Section 3.1.3 (Structures).

To use PAR on the U.S. vehicle, some means of making underwing blowing occur is needed. One simple, light and reliable means to this end with unmixed-flow engines is to rotate the canard. This is this writer's first choice and the Russians choice when consulted on how to vector on a unmixed-flow, commercial, fan engine. How to accomplish this via a rotating canard, turning vanes or whatever is Section 3.1.3 (Structures).

The unique U.S. noise problem for large WIGs

The initial WTET report identified the noise on takeoff from four or more large turbofans as a likely problem. Perhaps most germane to this problem is recognition that there is a definite state of the art in the U.S. today regarding the tolerable noise levels. NASA reports that part of the reason for relatively high airport noise allowances is public education and people living near airports are tired of complaining about noise. WIGs will operate from beaches and harbors, much of which can is high priced real estate. These locales are not airports which have undergone a "public re-education" campaign. We should expect less public tolerance for WIG noise than for aircraft. The trend is to set acceptable noise levels from sources outside the community (like military aircraft) at values less than that of softly breaking surf — under 70 dB at Malibu and Oxnard, California. DoD installations conducting air operations have had to curtail activities within a few miles of some beaches to no-afterburning, no-maneuvering flight. It seems reasonable to assume that this trend requiring DoD vehicles to be almost stealth-like in noise production will continue since federal activities have taken the apparent tack of embracing rather than rejecting environmental protection policies. Consequently, it is the expectation in this report that no large WIG noise abatement effort will ever satisfy many of U.S. coastal noise restrictions after 2000. This is because noise levels will continue to be set comfortably low for the residents, especially if real estate values are high. (The early stages of needed research and development would involve site-specific studies.) By 2000, a four-engined WIG might make 107 dB (plus augmentor noise) on takeoff and after Stage 4, possibly 100 dB to 102 dB. This is well above what the likely regulations will allow which makes takeoffs 10 miles from the beach and/or harbor the most likely resolution to the noise problem.

Noise from the basic or dry engine

Engine noise reduction research and development will be primarily an item for commercial engine development programs. The DoD will probably not have any impact on the basic commercial engine effort between now and 2000. PWA indicates that their 4000 series fan is inherently quiet, and both GE and PWA have been working for years to make their products quieter via blading aerodynamics, elimination of fan inlet guide vanes, increased rotor to stator axial spacing and acoustic hole treatments in nacelles and cowlings. However noisy the CF6-80, GE90, or PWA 4000 series engines are, these engines will represent the quietest available — which by Stage 3 definition will be no more than 101 perceived noise level (PNdB). All new engines for large aircraft must pass FAA Stage 3 noise regulations (FAR 36) for areas at or near airports. This applies to the CF6-80, GE90 and the PW4000 series. FAR 36.5 requires civil engines to be no louder than 101 equivalent perceived noise level (EPNdB) at takeoff for one engine. This equates to 104 for two, 107 for four, and 110 dB for eight engines at takeoff. The FAA does not allow for noise to rise beyond 106 dB on three or more engines. Since the FAA and NASA are presently discussing noise abatement at a Stage 4 level, large engine technology after 2000 may be even quieter than present large U.S. engines. The NASA research and development goal is about 10 dB less than 1992 values and is expected to be at 94 dB to 96 dB, which is considered "whisper" quiet, beyond 2000. No DoD involvement in noise abatement research and development is envisioned here, unless it is part of a 300,000 lbs dry engine for WIGs over 2,300 tons.

Augmentor noise

40% thrust augmentation is coarsely estimated to add another 4 dB to 6 dB, mostly low frequency, to the dry engine noise level. The augmentor has two noise sources. One is combustion low frequency rumble which exits the unchoked nozzle and has poor attenuation characteristics. (NASA Langley feels this

combustion noise will dominate.) The other source is the velocity differential which produces noise as a loss during mixing between the fan discharge nozzle and the mating core, and free streams. The 800° F fan nozzle gases will travel aft at roughly 1,365 ft/sec. This is cooler than many engine core temperatures at the nozzle discharge. One mechanism for noise reduction needing examination is mixing of nozzle air with external, low temperature, slow moving air over longer line lengths than a simple circular hole. Daisy or fluted mixers may be suitable. However, the effect of dilution or mixing of fan nozzle air with low energy free stream air reduces the "q" being delivered under the wing which produces lift via PAR. Careful assessment is needed so that PAR performance is not traded for quiet augmentation. If noise abatement research and development is unique to this burner, it would be a DoD task, since no other customer for such an augmentor is envisioned.

TATO as a noise and takeoff assist solution

(See Appendix B, Propulsion.) If TATO could be done, it might permit a 25% downsizing of the main propulsion engines by eliminating engines on the wing to provide 1.25% of required thrust in the event one of four engines fail on takeoff. Additionally, there would be large fuel savings by not using the main engines for taxi. A study assessing this has not been done.

Other environmental concerns (harmful combustion by-products such as dioxin from salt water combustion)

(See the WTET final report on this topic.) Today it is known that dioxin may, not will, be a product of gas turbine combustion on hydrocarbon fuels in the presence of salt water under certain conditions. Dioxin can increase the probability that various types of cancer occur in humans. In the U.S. today, credible individuals are available who are knowledgeable on both gas turbine combustion and how to conduct investigations on dioxin formation and mitigation. Such investigations, including tightly controlled combustion experiments, have not been conducted.

3.1.2.3 Development Required/Approach to be Taken

The principal development level envisioned for each topic is indicated as (6.X).

Sizing the engines

This 6.2 task needs input as to whether or not TATO, PAR or anything from the Takeoff Broad Agency Announcement will be used on the 400-ton WIG and what the takeoff demand will be for the main engines. Primary candidates (with PAR) would be existing commercial high bypass turbofans presently rated for aircraft at approximately 50,000 lbs dry at sea level static (SLS). It would be too late for a VCE study to provide the sudden revelation that such an engine is desired for our first vehicle. However, this is the time frame to run an important 6.2 study at NAWC/AD to assess the VCE usefulness for a second or third generation vehicle.

Engine Preselection Activities (marinization modification for 400-ton vehicle)

The first step, once the main engines are sized and candidates are identified, is the activity leading up to a technical (cost not to be a factor) competition for an engine selection. The principal activities described below are modest marinization, followed by a sea salt ingestion test. (The test described below would be done largely to establish the candidate engine's degradation rate due to salt deposits. Surge margin and exhaust gas temperature margins are expected to degrade. The winner would demonstrate the least

degradation after 12 to 16 hours of simulated flight operations.) The preselection activities to give the engine some degree of "salt hardening" could easily be advanced development.

6.3. Pre-test tasks include:

- trial coating applications for erosion and corrosion
- materials substitution
- derating by dropping the compressor operating line

Coating application and material substitution will be iterative activities. The operating line relocation will be nearly perfect on it's first build into an engine. The coatings effectiveness depends heavily upon the substrate to which they are applied and the non-lab nature of engine operation. Materials changes may or may not work on the first build. Further corrosion testing is not recommended as the engine can gain this experience in service.

The test program and engine selection (6.3).

Engine selection will be technically competitive. This will be based on a test conducted for the using agency seeking an engine with the best ability to retain desired operating margins in power and compressor stability over a long salty air mission. A test is needed to accurately predict how much and where salt will deposit in the gas path, and how much salt deposits will degrade flow areas and efficiencies. The engine manufacturer would make preliminary coatings and material substitutions prior to the test period, particularly since coatings will also degrade performance about 1% to 3%. Durability of some parts can be evaluated by teardown and inspection following salt air ingestion tests. The Russians should be funded to help design and run the test, plus evaluate results. The test (not mandatory at this stage) could also evaluate water wash schemes, probes, procedures, diagnostic software, starters modified for continuous duty and the starter air source, preferably with an onboard diesel or gas turbine. Water washing will be required to start each test sequence with a clean engine. Both washing methods and deposition assessment diagnostics might get their initial workout during this test. (A 6.4 effort to fully engineer these development issues would be expected to be delayed until Full Scale Engineering Development.) The Russians should also be funded to give guidance to all test programs regarding engine selection, except those regarding the TATO concept, where we probably know more about it. An engine type will be selected based upon these tests. The engine manufacturer should be paid for the use of one of their engine models, and all costs fairly associated with their participation. Only U.S. manufacturers should be allowed.

If TATO is used to meet the one-engine-out requirement and PAR is also used, the smallest thrust requirement for the main engines is produced — up to 25% smaller than the above 50,000 lbs dry case. If this occurs, the main air propulsion engines selected (with PAR) should be the most modern in the 38,000 lbs dry thrust class that have a strong relationship in cycle type to the larger PWA 4084 and GE90 series of commercial turbofan. This will likely be the PW2037 at 38,250 lbs. This engine should be put through the salt water hardening and ingestion research, development test and evaluation (6.3) program described above to determine if it can tolerate the sea environment. NAVSEA should be consulted about the suitability of the Allison 570/501K jet pump powerplant since it is already marinized, qualified for salt water ingestion and in use on seagoing hydrofoils in the U.S. Navy (USN) inventory.

Restoration of operating line margins from sea salt ingestion <u>(6.3 for initial experiments but 6.4 when results have to be engineered into the system in Full Scale Engineering Development)</u>

The Russians have made allowances for restoration of operating line margins from sea salt ingestion in their WIG engine design, operational practices and maintenance. They say they have verified their solutions by full scale testing. The first WTET final report deals with this in detail. Highlights of the Russian effort include:

- early engine sea salt spray ingestion tests to define the diagnostic signatures in operating line shifts
- the early engine sea salt spray ingestion tests to define effectiveness of daily fresh water washes to remove turbine vane area blockages and compressor blade salt deposits
- the use of sea water for washing in emergencies
- use of built-in wash probes inside the engine
- starter operation at lower than light-off rpms to allow continuous starter duty cycle
- elimination of the need for manual disconnects on engine sensor before and/or after a wash
- allowing (via a maximum thrust reduction) for a 150° F increase in turbine inlet temperature between washes.

This last effect is important in engine sizing and can be easily investigated with computer simulation built for that engine.

Fan Duct Augmentor development - <u>(6.2 through preliminary design and modest rig testing, 6.3 for full scale rig development, 6.4 thereafter for full scale augmentor development on an engine.)</u>

Assuming it will be desired to get a good early-on assessment in 6.2 of the difficulty of developing a fan duct augmentor before the likely engine is chosen, the likely engine candidates need to be identified based on a paper assessment. Some augmentor rig needs to be work done to establish this likely feasibility of the rig before development can be done for the selected engine. A range of rig conditions should be run to cover all likely engine candidates and unique augmentor schemes, if any, surface. A conceptual and preliminary design by each likely engine manufacturer is envisioned, followed by "parametric" rig tests to establish feasibility for their burner/engine. Conceptual formulation, preliminary design and the parametric rig work should be 6.2. More in-detail rig work could be 6.3, if the burner design looks promising. The 6.2 data generated should be convincing enough to take to the Triad decision point where concept feasibility is the issue. The engine company need not be the test data source, but the data generated must be believable to both the government and the engine manufacturer.

After the engine is chosen through the 6.3 tests, preliminary augmentor design would be revisited to identify any changes based upon the earlier, somewhat parametric tests. A full length, 45° to 60° sector rig of the experimental augmentor would be built in <u>6.3</u>. Rig development and critical features tests would be done with a realistic incoming pressure profile and temperature no higher than what the fan will deliver on a cool day. The engine manufacturer would recognize this as the start of serious augmentor demonstration and validation. Full length is required because combustion residence time does not scale. Full scale augmentor development on the engine would not start until Full Scale Engineering Development was begun on 6.4 funds.

Since augmentor development is expensive and this would be a burner unique to the WIG, some unusual funding sources might be considered. One suggestion might be to allow involved commercial entities to

form a joint development consortia under the National Defense Authorization Act P.L. 103-160, Sec. 845, which defines the authority of ARPA to carry out certain prototype projects for weapon systems. NASA has a similar authority under the 1958 Space Act. (See Appendix B, Propulsion.)

PAR Requires a Triad of 6.2 Success In Augmentors, Vectored Thrust and 800º F Fuel Tank Environment

It is important to note that the decision to go beyond 6.2 on the vehicle if PAR is elected is expected to be dependent upon two more items, in addition to the augmentor, being proven as feasible. In each case, feasibility should be based upon some proof of critical concept features. These three are:

1. thrust vectoring
2. no augmentor fire threat to wing fuel tanks
3. duct augmentor — the early-on rig test described earlier.

(It is assumed that PAR will be retested for a specific vehicle configuration as part of the vehicle development plan. The issue with PAR is not if it will work but simply installation factors to assure, for example, good tradeoffs between minimum thrust/weight ratio and desired takeoff and landing characteristics. This is a more comfortable risk level than with the above three. If any of the above three cannot be seen as feasible, then something in the overall WIG design must change until takeoff can be viewed as feasible with PAR. This three-way, or "Triad," proof of concept decision point is seen as the most critical technical milestone in the propulsion system development plan, if PAR is required. One need for PAR might be to optimize the vehicle for long range and lowest thrust/weight ratio required.

If PAR is not needed, both the thrust vectoring scheme and protection of the wing tanks will likely vanish as requirements. This would leave the vehicle to accomplish takeoff in some non-optimum way for that design, which might be perfectly acceptable. The Triad represents the most difficult but probably very optimum arrangement for lowest thrust/weight ratio and all the benefits downsizing the thrust requirements brings. It is an excellent critical path approach for a mutually supporting development program, which was the original planning objective, i.e. to give development priority to things that give the most flexibility to the WIG and are therefore probably the most difficult. The development level of the augmentor would be as presented above and that of the other legs on the Triad would be as determined by the vehicle program sponsoring them — however the Triad is conceptualized as a decision in 6.2, for all three items.

Once this Triad milestone is either successfully passed or circumvented by the adoption of a main mission that doesn't need PAR, one of the most technologically critical parts of the main propulsion development program are completed.

Environmental Research, Development, Test and Evaluation

The noise issue will likely be dealt with using onboard auxiliary engines providing taxi capability. However, if these engine are used for the TATO concept, enough 6.2 preliminary design work should be done to know how this will impact sizing the main engines. (Maybe not by Triad time but certainly before any milestone where approval is sought to buy main engines or start augmentor 6.4 development). The same can be said about any other takeoff assisted device that is to be depended upon to either add thrust or reduce any type of takeoff drag.

The following deals with hazardous chemical emissions from the combustion of liquid hydrocarbon fuel in the presence of sea water. (This is expected to be very 6.2 oriented work with any evident and promising mitigating solutions as excellent candidates for 6.3 funding and goal acceleration.)

The potential hazardous emission problem is seen as having at least two steps to a solution. The first step to comply with any hazardous emissions (including carcinogenic dioxin as an effluent), as perceived by DoD. Instructions, would be to determine if harmful species are or are not formed. The work to determine if a problem exists or not is:

1. Perform laboratory combustion tests with salt water sprayed into the air and puddled on and inside combustor liners and cases, or simulations thereof, to see if a harmful chemical species, not just dioxin, could be produced. A review of relevant combustion work would be appropriate through literature and known experts in this field. Simulating the environment inside the combustor during a one to two minute start with salt water puddled on the metal may be an important test.

2. Get sufficient test and evaluation in the lab to identify species, life spans of species and assess what it would be likely to do to humans. Try to identify and/or devise possible mechanisms for transfer of harmful emission species to the human environment. Try to develop some relatively simple techniques to avoid or somehow mitigate any harmful formations. Medical personnel would likely play a lead role in this step.

   At this point there would be sufficient information, including test data, to make the determination that, "Yes," there could be a problem or "No," no hazardous effluent is a likely product of gas turbine combustion operations on WIGs. If No, then all the steps below are eliminated and the issue is not expected to return. This would be considered sufficient to eliminate toxic emissions as a reason to not request approval for passing the next major acquisition milestone.

   If the answer is Yes, then we have a genuine "show stopper" until we can define "how bad" bad really is, and find and demonstrate a solution the medical personnel and the public are comfortable with. It is not possible to define today what the full impact of "Yes" would be on the overall WIG program. That question needs to be answered by a program review at that time. If the answer is "Yes" or even if it is only "very probable," Items 3 and 4 below should be accomplished. Item 4 would require the use of the selected engines for the 400-ton WIG and the results could impact further WIG plans. However, even if hazardous chemical emissions were formed in the lab, full scale vehicle research, development, test and evaluation might be done even if it were a violation of DoD directives. The authorization for this could come from PL103-160, Sec. 845.

3. Develop fieldable measuring equipment and check their suitability by going to the operational Navy using gas turbines to find out if any of the hazardous chemicals are being made.

4. Do extensive engine testing under simulated WIG "flying" and at rest conditions at AEDC in both light and heavy sea states to determine if engines can have a hazardous chemical formulation problem. It is mandatory however, that AEDC be advised of the potentially hazardous nature of such test and evaluation, with specific emphasis on the cancer deaths at Naval Air Propulsion Center, Trenton, currently named the Naval Air Warfare Center/Aircraft Division/Trenton (NAWC/AD/TRENTON) in the early '70s of four engineers and crew on an engine salt water ingestion test.

If there is a problem with no evident solution in hand, the allowance needs to be made in the program plan to make the decision to go on or to abandon WIGs propelled by combustion turbines. If the decision is to continue, then the second step would be to work out ways in the lab to mitigate the problems, preferably to

eliminate the formation of the pollutants. The third and final step would be to verify that the techniques are effective and adequate to the satisfaction of the project medical personnel and the public.

A contact on implementation of the first major step, at least Items 1 and 2 above, is Dr. Dave Pratt (University of Washington, Mechanical Engineering Dept., FU-10, Seattle, WA 98195. Phone: 206-543-4601.) The University of Washington (UW) has a combustion group for pollutants with both combustion and sampling equipment. They also have a medical staff who could provide much of the needed health physics protocols. Dr. Pratt was contacted on 20 May 1994 to determine their capabilities and interest, both of which were high since his field is combustion (specialty being gas turbines) and he has done a good deal of work for the Environmental Protection Agency (EPA) on the formations of dioxin from the combustion of chlorine bearing compounds.

Engine certification/development assurance testing with augmentor (strictly 6.4 work)

Following augmentor development for the engine, an endurance test would be conducted on a marinized version of the engine at worse-than-service conditions and performance levels, so the engine can be offered up for WIG service. The test should be geared to meet both military production and civil certification requirements. Several attempts at this test should be expected. Commercial certification practices rather than military specifications should be used wherever acceptable to the military. This includes meaning that the engine be run for certification at higher than in-service turbine inlet temperature levels, thrust and rpms and, then introduced to WIG use at 4,000 to 6,000 lbs less thrust. Endurance testing at AEDC should be done with salt water ingestion at median, not maximum, sea salt in air parts per million (PPM) levels and periodic washes. The manufacturer should run the certification test on the WIG mission cycle, as in commercial, without excessive low cycle fatigue testing. To ensure adequate fan stability margin, the augmentor tests should be run at the same height above ground as the WIG and the engine vectored down for "takeoff" for maximum inlet distortion if a tilting canard is used. The using authority may wish to certify that the marinized engine and augmentor meet service conditions for their intended use.

There should be a continuous push by the engine manufacturer to upgrade performance and durability in service to regain the "lost" thrust and to advance to higher thrust ratings as improved engine capabilities are available — without the need to fund the "growth step" to develop the uprating. This is a key cost avoidance methodology in commercial development that is not normally done in military development but is being suggested here for WIGs. For the manufacturer to want to do this requires that he be convinced there is a market for such engines, otherwise the military will have to fund each growth step ($120 million to 180 million each) plus planned product improvements ($5 million to $15 million per year). The benefits to the military of having a convincing mission, even a non-commercial one, are substantial.

3.1.2.4 Anticipated Program Accomplishments at Each Development Level

Assume the preceding propulsion work at the various development levels is organized chronologically. Thus, all the 6.2 work is done first, say in a Concept Formulation Phase, followed by all the 6.3 work in a Demonstration/Validation Phase, which then leads to the decision to enter Full Scale Engineering Development (6.4). The accomplishments expected from each phase as approval is requested to go to the next level of development are:

Accomplishments from the 6.2 Concept Formulation Phase

Concept Formulation is geared to provide early information allowing the program to deal with several uncertainties — one for the Triad in the event PAR is required and the others for noise and any other takeoff technology that might impact main engine sizing, and the last is toxic emissions from combustion in the presence of dissolved salts in sea water.

Assuming success, the following should be accomplished in Concept Formulation (6.2):

1. A range of augmentor and engine parameters to assess fan augmentation feasibility for specific candidate engine types has been tested on rigs. The burner data does not encompass all things but is adequate to make a reasonable judgment as to whether full scale augmentor development can start on large sector rigs once the engine is selected. These data can make engine selection input which would otherwise be based totally on salt water ingestion and/or deposition test characteristics described elsewhere.
2. There is adequate augmentor rig data and confidence in it to provide the "Triad Decision Point" for PAR operations with a reasonable assessment of fan duct augmentation feasibility. Hopefully, the thrust vectoring and safe fuel tank demonstrations of concept feasibility are also convincing enough to know that they are possible and the way is cleared to use PAR if required. (If the Triad fails owing to the augmentor it means bigger engines for takeoff by 40%, less optimum vehicle performance and probably an inability to do long range missions with any real degree of economy. If it fails by virtue of either the thrust vectoring system or if the fuel tanks cannot tolerate the hot gas environment of the augmentor discharge, then PAR can probably not be used.)
3. Any forms of takeoff assistance such as the or TATO, or concepts discussed in Section 3.1.1, Takeoff and Landing Technology will have generated sufficient output at the end of Concept Formulation to establish both feasibility and what the size the main engines must be on takeoff. Sizing results in the selection of at least one and possibly several candidate engines for competitive testing in Demonstration and Validation (6.3).
4. Sufficient combustion experiments conducted to identify whether there is or is not a problem with formation of combustion species hazardous to humans. If none are formed or if the formations are not hazardous, then this is the end of this line of investigation. If a hazard is formed, but a promising plan developed to show a line of research and development that might mitigate this hazard, then either more Concept Formulation (6.2) funds are needed or this plan is advanced into Demonstration and Validation (6.3), depending upon how sure the solution appears.

Accomplishments from the 6.3 Demonstration/Validation Phase

1. The best available engine (least loss of critical operational margins) will have been found based mostly upon the reality of affordable salt water ingestion testing, probably at AEDC. The testing will also provide information on corrosion resistance and what is required to restore these critical margins via washing.
2. By building and testing critical full scale (length and radius) augmentor components in a sector rig geared to the selected engine, we know that cruise will be with possibly 15% to 20% less fuel consumption than the Russians could have gotten with the same basic engine cycle and more dry thrust on the wing. We will have reduced the number of engines or dry thrust on the wing by 40%.
3. A related vehicle program is TATO. If TATO is selected, this feature will provide not only environmental noise protection but also up to an additional 25% downsizing in air propulsion

engines and their costs, weight, drag and servicing requirements with no safety reduction. TATO could easily start with some Concept Formulation (6.2) and/or Demonstration/Validation (6.3) work ranging from sizing, preliminary design on through jet pump weight reduction.

4. The combination of augmentation to reduce dry thrust required by a factor of 1.4 and the use of TATO to reduce it further by up to 25% effectively would let American WIGs with PAR use only 55% of the dry thrust of any other country on this vehicle type. Our relative standing on propulsion capital costs and range should be substantial. If PAR is not used, multiply the 55% by [(.35 to .4) /.25 = 1.4-1.6] = 0.77 - 0.88, which leaves us with an advantage in propulsion weight and cost over other countries via good engines, TATO and an augmentor of 12% to 23%. This is a marginal advantage and highlights the benefits of well applied PAR.

<u>Accomplishments from the 6.4 Full Scale Engineering Development Phase</u>

1. Once the engine and/or augmentor has passed the equivalent of a preliminary flight rating test (PFRT), usually a 60-hour endurance test, the engine with augmentor can be shipped to the vehicle for flight tests.
2. At the end of the engine Full Scale Engineering Development, the augmentor will be fully developed on the engine and an endurance type test will have been done on both over simulated mission conditions including salt water spray ingestion. Sufficient test and evaluation will be done to permit FAA certification — if a civil mission is envisioned or if civil support is sought. The engine will be fully capable of critical operational margin restorations (surge, exhaust gas temperature [EGT]) via water washing in the hour after tying up at the dock with minimal fresh water and help from dock hands. Availability will not be adversely effected by the need to wash engines even if washing is after each flight.
3. An Integrated Logistic Support (ILS) plan will be developed. It will make simultaneous replacement of all engines a favorable choice over individual removal and replacement as required because it supports squadron/operational personnel and places supply chain convenience secondary. The more engines the WIG has, the more important this becomes. This maintenance concept must be built into the ILS plan or else it will be as indicated and availability will suffer to the point of loss of the vehicle as a useful entity.

3.1.2.4 Cost and Schedule

<u>The Concept Formulation (6.2) Propulsion Subtasks are:</u>

1) Fan Augmentor feasibility assessment and/or rig parametric tests

Select likely candidate engine cycle characteristics (best guess) no less than 11 months prior to Triad meeting using the best inputs vehicle program can make regarding envisioned success with takeoff technology, vectoring and fuel tanks. Emphasis here is not on engine size but cycle specifics so that parametric augmentor rig tests can be useful. Put both PWA and GE under contract for preliminary design (PD) and rig tests. (Costs below are two company costs.) Allow six months to accomplish this contractual subtask with Subtask 5 team.

PWA and GE preparation for 30-day kickoff meeting		$50,000
Make preliminary designs for candidate engines	2 months	$100,000
Make assessment of augmentor critical technologies	1 months	$50,000
Determine feasibility for applicable engines via rig tests -includes pitch prep and give to Triad meeting,	6 months	$1,650,000
Assess best candidate engines for augmentor if possible -	1 months	$50,000
Define requirements for augmentor research and development in 6.3	2 months	$100,000

In all, allow 18 months and no less than $2 million for this activity, which should start with the 6-month task of getting PWA and GE under contract, sub-contract or some form of agreement to ARPA. Assume a start on this immediately after a kickoff planning meeting 30 days from program start.

2) Resolution of propulsion sizing issues so the selection of engine candidates and augmentor conceptualization can proceed.

From the vehicle program, and outside the funding of this section, come the following activities:

- Takeoff technology concept definition and takeoff thrust contribution
- Proof of takeoff technology concept(s) feasibility
- Thrust vectoring concept definition
- Proof of thrust vectoring concept
- Fuel tank thermal protection concept definition
- Proof of fuel tank thermal protection feasibility
- Reassess requirements and/or contributions from PAR

An input from the above activity constituting a best guess on their expected success or failure with Triad issues will need to be made no less than 10 months before the Triad in order to do the parametric augmentor rig tests above in Subtask 1 and the preliminary engine salt hardening planning below. The alternative is to wait until vehicle portions in parallel with Subtask 2 are complete before beginning the augmentor rig program.

The propulsion portion of the plan will provide:

- Manpower to interface with the above and test plan
- Determine one-engine-out main engine thrust needs
- Identify engines in this thrust class (the candidates)
- Fund at least two engines for salt water ingestion hardening planning — determine salt water test plan and water wash procedures, define coating and material changes desired, define turbine vane area machining changes to open area and drop operating line (price a new vane hardware set and costs for other mods to be borne in Phase 2.)
- Coordinate probable test with AEDC.
- Do VCE analytical investigation for 2nd/3rd generation.

The first four propulsion plan items above can be done for $80,000 plus $120 for the 9-month Navy VCE study by NAWC/AD (The point of contact at Trenton is Andy Rutherford who will need to be advised to submit a work unit plan for this effort.) The salt hardening planning and AEDC coordination, however, should take six months and $500,000 per engine ($1 million for two engines). Total Task 1 costs are $1.2 million. The time for the vehicle items will be the pacing factor to arrive at a completion date for this 6.2 task.

3) The Triad decision point for PAR

- Present feasibility of concept data on three items
  - Fan duct augmentor
  - Thrust vectoring scheme
  - Fuel tank tolerance for augmentor discharge
- Assess whether or not PAR and the Triad elements can be used and should be keystoned into the design.

The propulsion costs would be costs to prepare for and attend a major meeting — time would be concurrent, costs about $20,000. Add one month and $20,000 for post-meeting assessments and a second get-together to thrash things out before a final Triad decision is made. Total task cost is $40,000.

4) Toxic sea salt combustion issues

- Establish funding to an organization to run/manage this. Allow six months to create a contract/sub-contract or agreement. Engineering time to pick the right entity (titled "selectee" below) with both medical and combustion skills and get the funding mechanism in place. This task should start at the beginning of the overall propulsion 6.2 phase.
- Selectee writes and submits plan to assess threat (one month, $60,000). A dialogue on specific toxicity concerns begins with EPA and close coordination is established with them.
- Do analytical and lab plus literature work as appropriate to make an assessment whether there will be a toxic combustion problem with sea salts in ingested water. 17 months, $3.5 million.
- Hold public meeting on results of above regarding the likelihood of a toxic emission problem. Consider a likely future WIG site for the meeting. Two months, $300,000.
- Receive comment from public

  If there is no evident toxicity threat, then this ends this project's work on the topic. However, if the issue cannot be clearly settled as a non-threat, then proceed as follows:

  - make operational combustion emission mitigation plan and prepare to do sampling of real hardware and at sea. Equipment and procedures to effectively eliminate the threat will be developed in 6.3 if they can be conceptualized here, and demonstrated/validated later in the next phase.
  - review plan and comments with EPA and DoD.

    Allow six months and $400,000 for the above.

  - If results show a likely hazard , hold major program review to determine impact upon the WIG project. Recognize that under PL103-160, the program could probably be continued despite potential problems if ARPA wished to. Four months, $500,000.
  - Make this and the mitigation plan public information

Total subtask time and cost are either 25 months and $3.86 million or 32 months and $4.76 million, depending on whether a toxicity problem requiring mitigation is found.

5) TATO - Size and identify critical technology features. $1 million

6) Contract/project management and coordination to monitor all the above and keep it coherent. $250,000 per year or $60,000 for 32 months.

Total Concept Formulation Phase 1 (6.2) costs for this subtask can be a maximum of $8.67 million, time is 32 months.

The Demonstration/Validation Phase 2 (6.3) Subtasks are:

1) 30-day planning and kickoff meeting. $80,000.

2) Harden the two candidate engines for the salt water ingestion test and drop the operating line. Consider the corrosion aspects of hardening to be preliminary, since corrosion is not the big issue here but performance degradation from salt ingestion is. Thus we will concentrate here on rework of the turbine vane entry flow area, coat where we have to in the fan/compressor and change materials if feasible (three months concurrent with turbine work below and $600,000). An objective will be trying to avoid ordering long lead time parts although we must be prepared to order both at least a new set of first stage high pressure turbine (HPT) vanes for each engine. Since these are nickel alloy castings allow at least one year for this, possibly 18 months. (Picking an engine still in production would possibly let us interrupt the lines "parts received and waiting for machining" bin for a no-time delay. We will plan on getting our vane set for broaching a different vane angle this way.) The cost for a large Turbofan high pressure turbine (first stage (TF HPT1) vane set would be on the order of $350,000 per engine plus $50,000 and one month for vane rework. Allow another three months for engine build-up and shakedown tests by the manufacturer. in preparation for the actual salt tests at AEDC ($300,000). If in-situ water wash probes are to be used, build-up is the time when they need to be installed, after extensive shake table testing to ensure no resonances in the operating range. In situ probes should be considered a high foreign object damage risk item. Engine acquisition costs, exclusive of the above hardening, are most difficult to estimate because they depend more on the perceived market the engine manufacturer sees for WIGs than actual costs to produce the engines used. For the test program, only one engine of each candidate is required. The costs could be as low as zero for a loaned engine, $4 million for use and post-test refurbishment to $6 million to $8 million per engine serial number for an outright purchase in the 50,000 thrust dry class. Assume refurbishment costs for both engines, i.e. $8 million for engine acquisition costs. Total subtask time is no less than nine months and pretest rework costs after acquisition will be $1.3 million per engine. Use one year to allow for minor contingencies including fitting into the engine manufacturer's commercial schedule. Total subtask costs including acquisition and rework to deliver two semi-salt hardened test articles to AEDC will be $9.3 million.

3) Salt water ingestion testing - Allowing nine months of preparation at AEDC before the engines arrive (including salt mist rig development with some cell occupancy for $4,000), and eight months of engine occupancy (four months each) for 200 to 300 test hours on each of two different engines, the AEDC costs would be on the order of $8 million, which may have to have some salt water combustion mitigation facility modifications (allow an additional $2,000 and 12 months concurrently for this). Anticipate that NAWC/AD personnel from their regular AEDC contingent will likely assist NAVSEA run these tests at a net cost via a work unit plan (WUP) of $200,000 per year above the $4 million per engine test costs by

USAF. Allow 60 days for teardown and inspection of each engine at a cost of $600,000, including NAWC/AD and engine contractors.

The output of these tests would be a recommendation as to which engine is the best suited for high sea-salt-in-air environment operation with the least performance loss, and least likelihood of surging the engine or exceeding exhaust gas temperatures despite extended mission times of 12 to 16 hours with no washes. Allow 60 days and $400,000 to resolve these data into a decision.

Allow 24 months and $15.4 million for this test and evaluation task.

4) **Full scale augmentor rig development** - Once Phase 2 is entered, both engine contractors are to be funded to complete a full scale length and radius sector augmentor rig design with realistic entry pressures (and their profiles) and temperatures. All rig design and test planning work to develop a good full scale augmentor for the fan duct shall be accomplished before the salt ingestion tests and their selection decision are made. The objective is to have all prehardware rig efforts done when the engine is selected by test and then proceed into the augmentor rig hardware program with the winning engine. Allow four months and $500,000 for this, including design of some new rig facility parts.

Once the losing engine is eliminated and authorization to proceed is given to the "big rig" program, long lead parts and test equipment are ordered. Since this should be mostly sheet metal and noncastings, allow six months for all needed hardware and equipment to arrive for assembly then test one month later ($1,000). Allow six months for rig developmental tests to establish the full scale design needs of the real augmentor.($1,500). Allow four months for design based upon rig tests of an augmentor ready to enter engineering development ($500,000). Total subtask time will be 26 months from the date engines are shipped, cost will be $3 million.

5) **Combustion toxicity mitigation** - This subtask is omitted if there clearly is no problem found in the salt water combustion work at UW in Concept Formulation. However, if the program viewpoint is that the mitigation plan developed in 6.2 must be pursued, then this must be started early in the Demonstration/Validation phase. The engines on test with salt water ingestion at AEDC should be used as a sample source and should be instrumented accordingly from this subtask. (Recall that $2 million was allocated in the salt water test for facility modification to mitigate any such problem if this could be defined early enough. With the disclosures on this topic as visible as planned, it seems probable that AEDC management or the blue collar Union will demand mitigation as a precursor to testing.) Allow $6 million and 28 months for the development of sampling methods, detection and mitigation at AEDC to demonstrate success, including 10 months of data collection, public review and comment, and development of a mitigation plan for the engine testing with salt water ingestion at AEDC in Full Scale Engineering Development, Phase III. Once detection protocols are developed, the detection equipment should go to sea with turbine powered military ships which ingest significant amounts of sea salts — DD963's for example. Sea trials would determine if the equipment could function reliably in such an environment, with results confidential to the service generating the samples.

6) **TATO** - Design, fabricate and test critical technologies. $4 million.

7) **Contract/project management and coordination** - To monitor the above and keep it coherent. $250,000 per year for 40 months, $900,000 total.

Overall Phase 2 time will be 44 months. Total Phase 2 Demonstration/Validation (6.3) costs will be $38.6 million.

Full Scale Engineering Development (6.4) Phase 3 Subtasks are:

1) **Augmented engine development through PFRT (60-hour preliminary flight rating test)** - PFRT is the performance and reliability milestone where the engine is considered satisfactory for first flight tests and technical evaluation on the WIG via a Navy test and evaluation organization. Following the salt water test and downselect to a single engine, once 6.4 is entered, the engine manufacturer will use the test and teardown inspection information to identify changes to the existing design to make it suitable for the WIG environment. Concurrent with a design and review of this new engine model, with augmentor, development to PFRT proceeds, with potentially substantial engine changes to accommodate salt and regular washings, and diagnostics thereto. Assume two years to PFRT with several full scale tests of 200 to 400 hours duration under mission conditions with sea salt ingestion and one final test with sea salt at rated turbine inlet temperature (TIT) + 50° F of 60 hours with pre- and post-test performance checks, and post-test disassembly and inspection. All full scale engine test and evaluation should be at the same facility where salt ingestion selection tests were done — likely AEDC. This is because that facility will have undergone emission mitigation treatment and should be safe for that type of testing. To activate the Phase III toxic emission mitigation plan written for AEDC in Phase II, assume another $6 million for facility enhancements. Assume about two years at $45 million per year plus $5 million per year AEDC costs (which will include $500,000 per year for toxic emission monitoring, separate from the facility enhancements above). Total $106 million through PFRT.

Approximately eight PFRT configuration engines plus two spares (10 total) will be shipped to the WIG test article, at an assumed cost of $10 million each ($100 million for 10 engines), billable to the flight test program.) Note that all 10 engines should be through a modest parts reconfiguration for items that had to be changed as a result of PFRT, but by the 31st month of the Full Scale Engineering Development program, all 10 engines have been delivered to the test WIG for flight test. The test and evaluation program for the WIG should not fly the engines more than 200 hours before they are removed and returned for overhaul.

2) **Augmented engine development through a limited production decision** - This will take two years and should be considered as a candidate for commercial, not military, development practices. The output will be an engine slightly downrated (but not below Table 3-3) to achieve durability with excellent potential to have performance continuously creep up as operational and flight test experience tell the manufacturer where to put his efforts to raise durability with performance. The output of the 6.4 program fed by flight test and AEDC salt ingestion tests of the post-PFRT engines will be an engine model with probably no less than PFRT performance but better durability — good for 400 to 600 hours on the wing before removal. (The Russians remove theirs at 400 hours.) Allow 24 months and another $90 million for the manufacturer and $30 million for AEDC, Total $120 million.

3) **TATO** - Build and deliver 1 1/2 hardware sets to flight test vehicle

4) **Contract/project management and coordination** - To monitor all the above and keep it coherent, $250,000 per year for 48 months, Total $1 million.

Total Phase 3 time will be four years and costs will be $227 million.

Overall Propulsion (6.2 - 6.4) times and costs will be:

Phase	Time in months	Cost
1. 6.2 Concept Formulation	32	$ 9.87 million
2. 6.3 Demonstration/Validation	44	$38.60 million
3. 6.4 Full Scale Engineering Development	48	$243.00 million
Totals	**124 months**	**$291.47 million**

The following program charts show the time layout of each task and subtask.

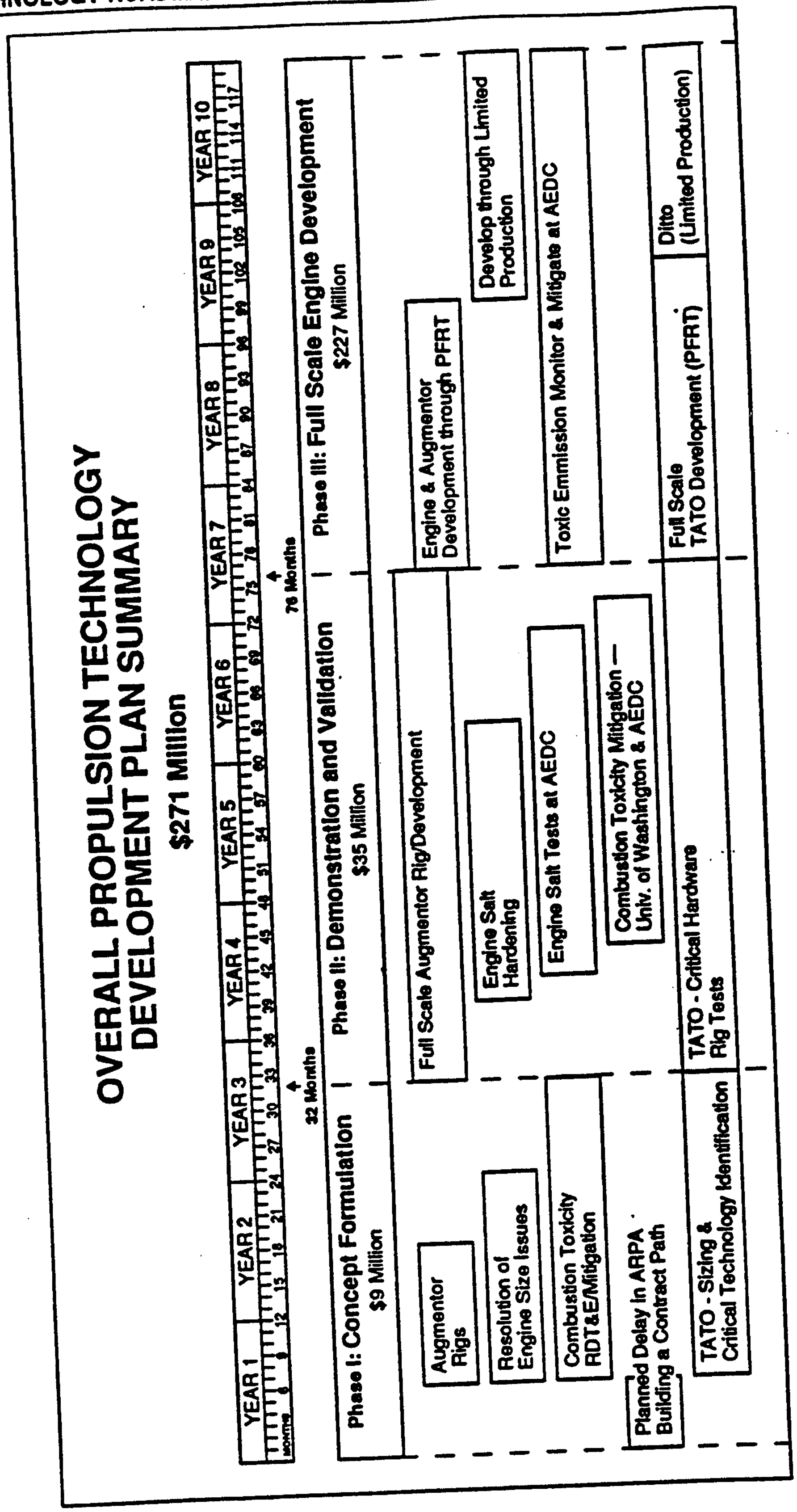


Figure 3-9 - Overall Propulsion Technology Development Plan Summary

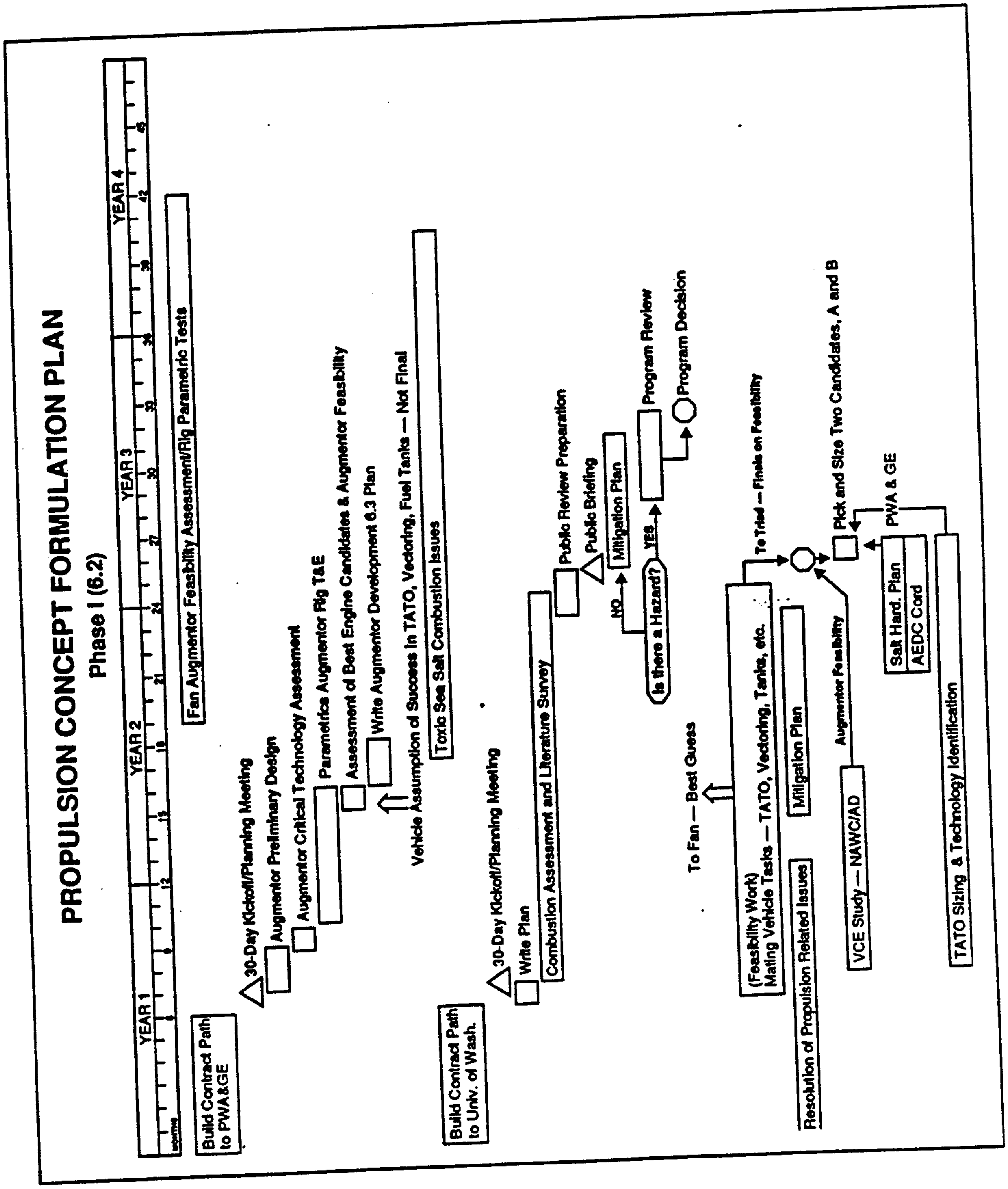


Figure 3-10 - Propulsion Concept Formulation Plan

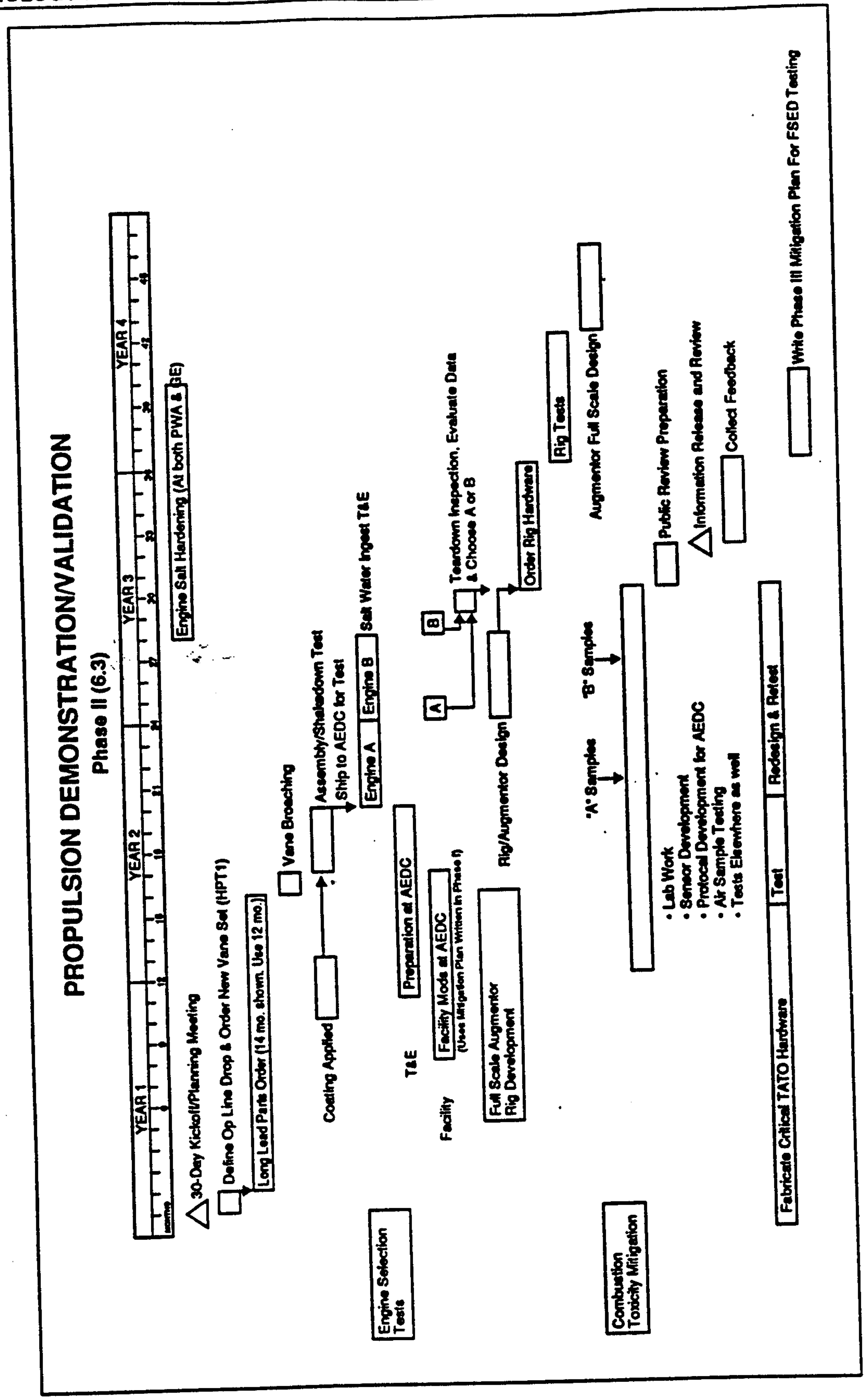


Figure 3-11 - Propulsion Demonstration/Validation

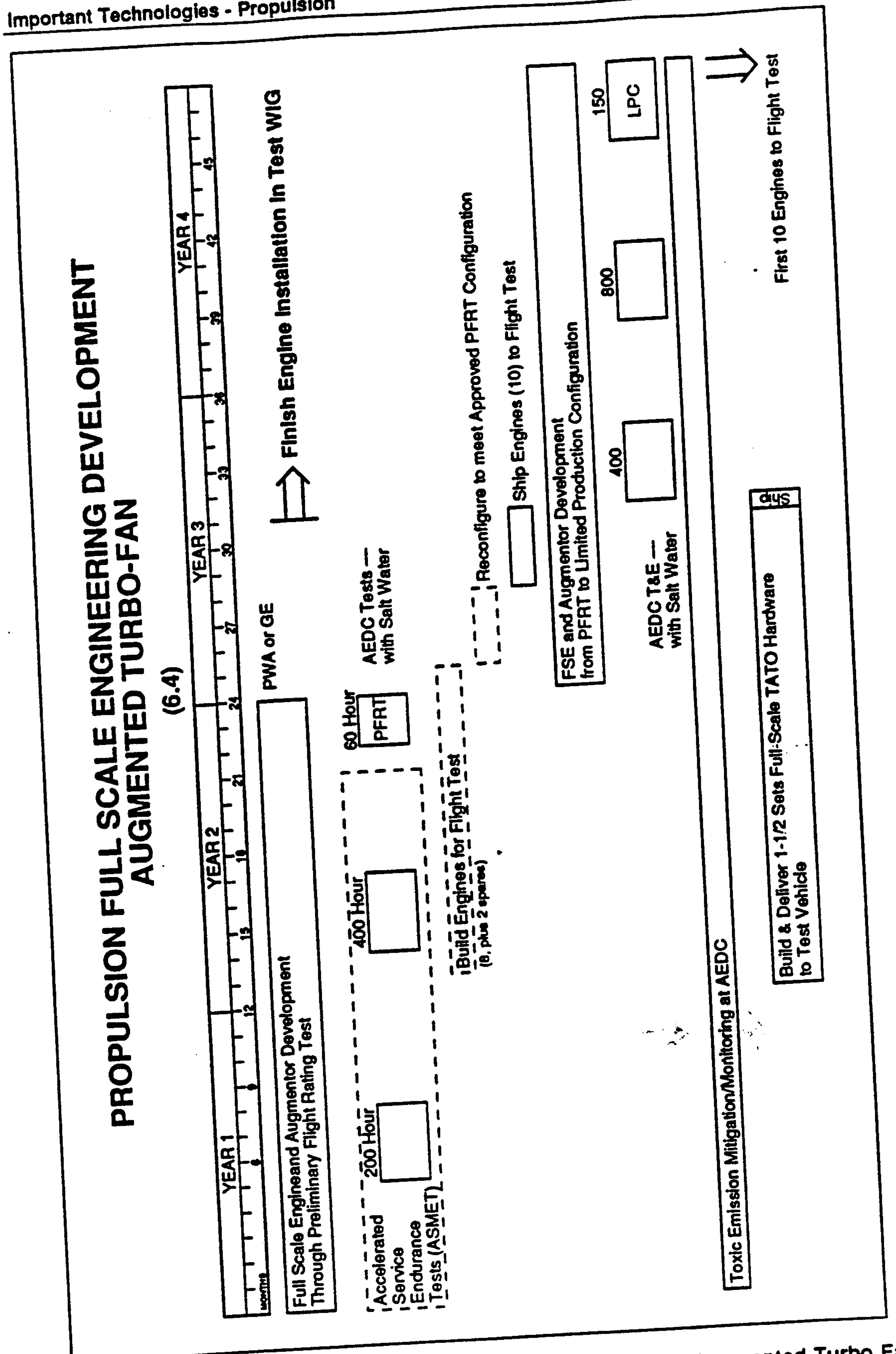


Figure 3-12 - Propulsion Full Scale Engineering Development/Augmented Turbo Fan

3.1.3 Structures

This technology roadmap for structures discusses wingships from 150 Ltons to 5,000 tons. in size. (Note: tons are short tons.) The empirical basis for this roadmap is limited since the largest wingship built to date is the Caspian Sea Monster with a full load weight of only 540 tons. The ORLAN and LUN wingships were about 150 tons and 400 tons respectively. Several U.S. designs have reported sizes ranging from 590 tons to 1,000 tons. These consisted of the Douglas Aircraft Wingship-O 1,180,000-lbs design (for Out-of-Ground-Effect operation) under Advanced Naval Vehicle Concepts Evaluation (ANVCE); Lockheed-Georgia 1,362,000-lbs "Spanloader"; a Lockheed 1962 design of a "Winged Hull Vehicle" at 1,800,000 lbs; and a Douglas Aircraft 2,000,000 lbs design of a WIG-S, also performed under ANVCE. Recent information on an informal Northrop wingship of 1,600,000 lbs is also included.

3.1.3.1 Requirements

Structures requirements are based on the utilization of Power Augmented Ram (PAR) for takeoff assistance, and the use of a hydroski or other devices for landing. These features may have considerable impact on loads imposed on wingship structures during landing. The latter, particularly, is critical and a determining factor in structural large wingship design. Emphasis is on estimating loads and reducing structural weight to achieve the relatively high payload fractions necessary to obtain the full benefits of the wingship concept. It will be necessary to be able to accurately estimate vehicle empty weight at least several years prior to the start of engineering development. This ability, normally well within the capability of the aircraft industry, will be severely hampered when the vehicle employs the following characteristics:

1. A high percent of composite materials in the structure itself (typically at least 45% to 55%)
2. A perception of vehicle structural needs which drives either the developer or the resin producer towards a new family of resins with uncertain characteristics in allowables and producibility. The risk of entering engineering development with resin/matrix properties in allowables or producibility impacting weight that the still being defined in unacceptable.
3. Large composite structural sizes and shapes which are not in the actual composite manufacturing experience of the developer.
4. A configuration other than conventional wing-fuselage-tail, i.e. one in which the usual parametrics used prior to actual structural design are not in the developers experience base.
5. When one of the "illities" can have a significant and adverse impact upon weight if it's system engineering needs are not acknowledged and accommodated in the preliminary vehicle design.

A detailed recommended experimental and analytical loads program is included under 3.1.3.5

For the 400-, 1,000-, 2,300- and 5,000-ton wingship alternatives, a high priority will need to be placed on advanced high-strength lightweight materials and structural design methods. The larger wingship structures will require advanced aluminum, titanium and composite materials. It is evident that a requirement of future large wingship design that the large differences be fully understood between projected structural weight and empty weight values, and those actually achieved for the ORLAN and LUN wingships. Modern composites with imbedded boron fibers (expensive), carbon, graphite and Kevlar fibers have lead to significant (about 25% to 30%) weight savings over conventional aluminum. The increased cost associated with composites could be dissipated by reducing structural pieces, component commonality and structural

simplification. Modern composite matrix materials such as thermoplastics, metals and polyimides could lead to even lighter wingship structures. Detailed analysis and design using these materials is required.

Substantial analysis and testing will be needed to utilize advanced composites technologies for wingships. Unlike metals, the strength and stiffness of advanced composites can be tailored to meet load requirements. Research and development is critical in preventing problems from environmental heat and moisture, fatigue and slamming damage, and delamination failure.

Development is required for the effective use of sandwich core material in the fuselage, wings and appendages particularly for the 2,300-ton and 5,000-ton wingships.

Special attention should be given to Mission Required Capabilities

3.1.3.2 State of the Art

An information summary regarding structures on existing large wingships and projected designs is included here for background information.

The Russians attempted concept demonstrators, ORLAN and LUN, and neither concept became operational. The reason for these craft not becoming operational may be either concept deficiencies or general conditions in the former Soviet Union.

As pointed out in the wingship report, Reference 1 (page 94), it is not clear that the technology base exists to support design of a wing-carry-through-structure of modern lightweight materials. Hence, a sequence of "Technology Demonstrators" may be appropriate to provide a technology base to ensure that a lightweight structure can be built for wingships of 1.6 million, 6 million, and 10 million pounds.

Reference 2 describes Soviet wingships and points out that one main problem creating a large wingship is structural design. The authors emphasized the following:

- Minimum mass for unit structure and for the wingship as a whole;
- Optimal combination of structure and payload volume utilized for the particular load, crew, equipment;
- Consideration of production and operating technology requirements;
- Necessary rigidity of the structure, taking into account the dynamic load and the means of damping for the purpose of static and dynamic stability of the structure during flight;
- Wingships, like modern aircraft, require high tech solutions and complex subsystems. In addition, wingships, which operate on the border of two media, water and air, are complicated by the requirement to operate in unfavorable corrosion conditions. This condition creates extremely stringent requirements for hull structures design, particularly, while ensuring structural weight efficiency.
- Given the above issues, special attention should be directed toward choosing construction materials, which in turn determines to a great extent the optimization possibilities of not only the structures, but also of the wingship as a whole.

"ORLENOK" (Orlan) Wingship

An overview of the 150-ton ORLAN is given in Figure 3-13, which is taken from Reference 3.

The ORLAN, also called the A.90.150 EKRANOPLAN, has the following principal characteristics, according to References 3 and 4:

Overall length	190.3 ft; 58.0 m
Wingspan	103.4 ft; 31.5 m
Height	52.5 ft; 16.0 m
Fuselage length	151 ft.; 46.0 m
Wing area	3218 ft^2; 299 m^2
Horizontal tail span	85.3 ft; 26 m
Horizontal tail area	1300 ft^2; 120.7 m^2
Weight, normal takeoff	110 tons
Weight, overload takeoff	125 tons (with restriction in wave height during takeoff).
Engines	two Kuznetsov NK-8 turbo-fan engines, up to 10.5 tons thrust, for takeoff; one Kuznetsov NK-12, 11,000 kW, turboprop for sustained cruising.
Speed, cruising	400 km/h; 216 knots
Range	2000 km, 1080 n miles
Fuel load for normal takeoff weight	15 tons
Fuel load for overload takeoff weight	28 tons
Sea flying limit; takeoff and landing	"Force 4" (Seastate 3)
While afloat and flying	"Force 4 to 5" (Approximately Seastate 4)

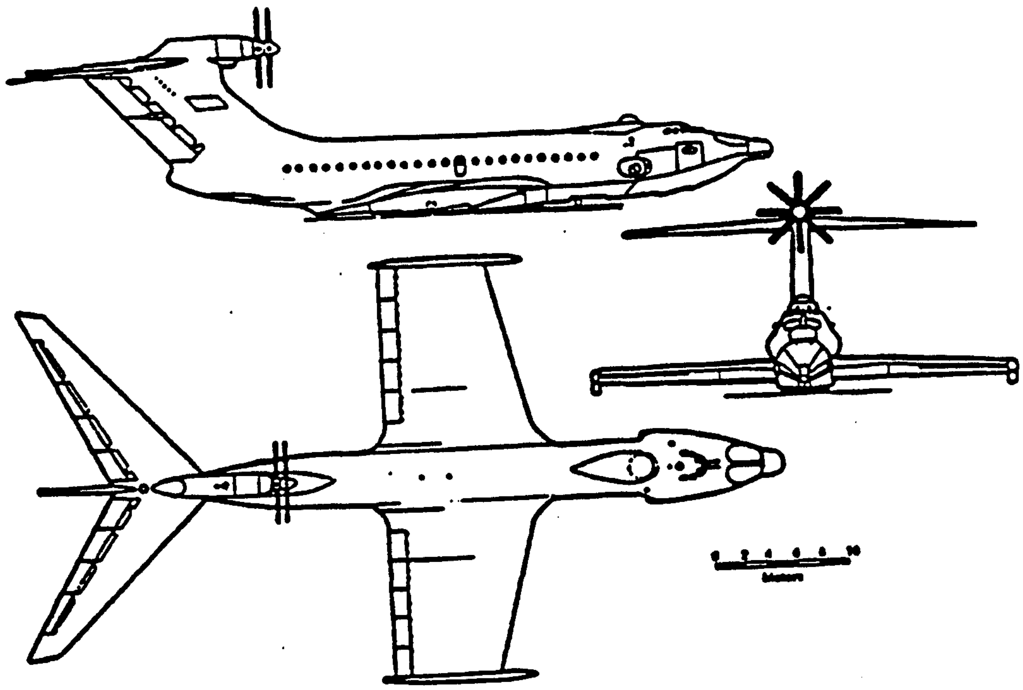


Figure 3-13 - Overview of ORLAN

"The fuselage is of a relatively simple girder and stringer design and like the wings, is divided into watertight compartments." Note that this is a welded structure.

The NK-12 turboprop installation is mounted high at the fin and tailplane intersection in order to keep the intake as far away from sea spray as is feasible.

The nose-mounted jet engines have pivoted exhaust nozzles. During takeoff, the jet exhaust streams are directed beneath the wing to boost the ram-air pressure beneath the wing. On changing to cruising flight the nozzles are redirected to provide horizontal thrust accelerating the craft until cruising speed is reached. The takeoff jet units are then shut down. The fuselage nose location of the jet units allows their intakes to be positioned in the contours of the nose in such a way as to minimize aerodynamic resistance.

Several independent weight breakdown estimates were made of ORLAN by WARDIV, NAWC, and CARDIV, NSWC. WarDiv, NAWC estimated the characteristics of the ORLAN, including weight estimates of the structure; and the mechanical and electronic systems. Commercial aircraft structural design techniques were used for the structural weight estimate with strength and weight added to account for the increased loads from sea-based operations. Included below are the three WarDiv, NAWC weight estimates for the ORLAN with the CARDIV, NSWC weight estimate for comparison.

ORLAN WINGSHIP VEHICLE WEIGHT ESTIMATE COMPARISON

COMPONENT	WEIGHT (lb) WARDIV, NAWC			CARDIV, NSWC
	LOW	MID	HIGH	
Fuselage	23,415	37,316	41,048	51,216
Wings	24,770	35,925	43,428	27,240
Endplates	4,796	8,344	13,957	7,2880
Horizontal Tail	7,759	10,200	11,220	9,500
Vertical Tail	2,000	3,550	3,905	2,954
TOTAL	62,740	95,335	113,558	98,190

Subsequent to this study, the wingship team was advised by the Russian wingship experts that the structural weight fraction of ORLAN was 34%. (Reference 4.) This equates to 74,800 lbs based on normal takeoff weight of 110 tons, or 85,000 lbs based on overload takeoff weight of 125 tons. Apparently the WarDiv, NAWC low- to mid-range calculation bracketed these values rather well. As an aside, the Russian value for the ORLAN empty weight fraction was reported as 50%. (Reference 4.)

LUN/SPASATEL Wingship

LUN is shown in Figure 3-14. SPASATEL was built to the same basic design as a rescue vehicle, but was not completed.

Principal Characteristics of LUN are:

Total full load weight	400 tons
Length, overall	242 ft; 73.8 m
Beam/Wingspan	144 ft; 44 m
Wing chord	43.6 ft; 13.3 m (estimate based on Aspect Ratio of 3.3)
Height, overall	63 ft; 19.2 m
Draft, hull borne	8.2 ft; 2.5 m
Power plants	8 NK-87 type turbofan engines, each with a maximum static thrust of 13 tons (26,000 lb.)

No structural weight analysis of the LUN has been made by the WTET. The Russians told the U.S. team that the structural weight fraction of LUN is the same as the ORLAN — 34%. This would be about 272,000 lbs. Empty weight fraction was reported as 50%. (Reference 4)

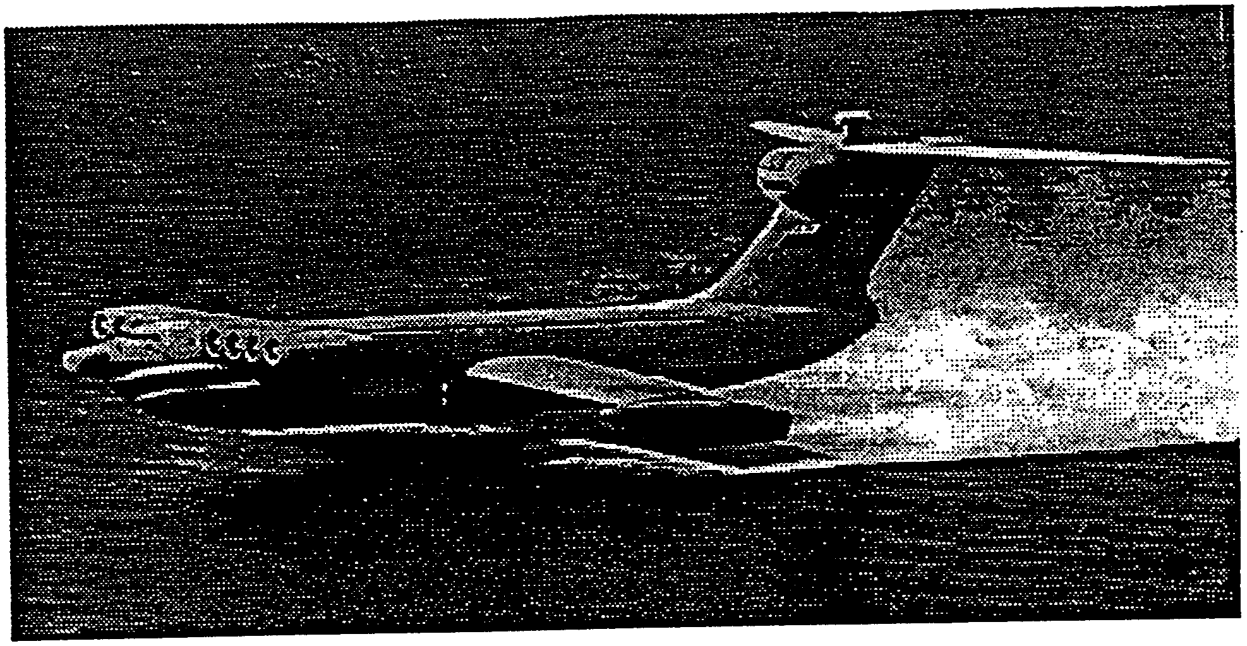


Figure 3-14 - LUN

Lockheed-Georgia Wingship

It should be borne in mind that the Lockheed vehicle, described in Reference 5 and shown in Figure 3-15, was analyzed without benefit of recent information and knowledge from various Russian ORLAN and LUN wingship experts.

The Lockheed 1.362-million-lb wing-in-ground-effect (wingship) was designed as a logistics transport capable of transporting 441,000 pounds (200,038 kg) 4,000 nautical miles (7,408 km) over an open ocean in a Seastate 3 environment at a cruise speed of 0.40 Mach. Power Augmented Ram (PAR) is provided for the takeoff and landing modes. Payload containment is provided within the wing contour and is distributed over the full span of the wing. The forward fuselage contains all required crew accommodations necessary for the 15-hour design mission. The forward fuselage also provides support to the main propulsion system in a location forward and above the wing leading edge as required for power augmentation during the takeoff and landing modes. The twin vertical and full span all-movable horizontal empennage is supported from the wing trailing edge by twin tail booms.

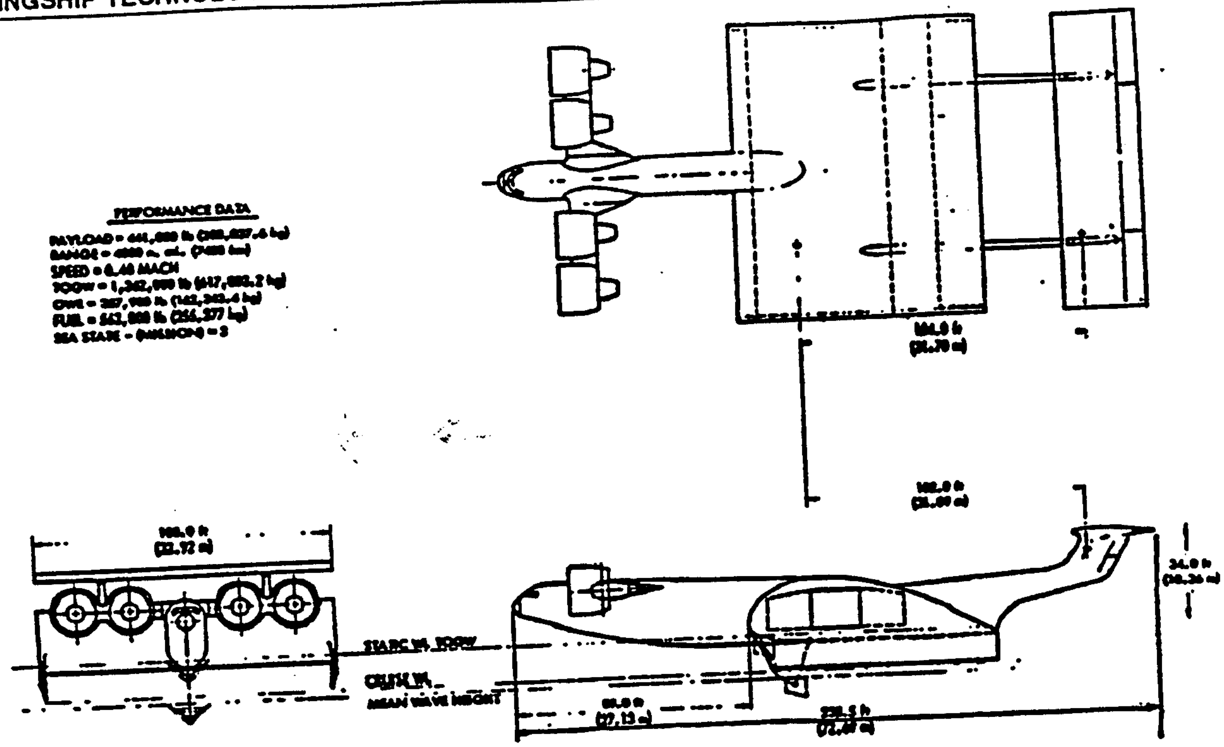


Figure 3-15 - Lockheed-Georgia Wingship

Structural Aspects

Wing Loads - Wing loads for the final Lockheed wingship configuration were somewhat lower than expected on an aircraft of this size. This was due to several factors. The short wing span, which was a fixed study parameter, did not allow bending moments to build up to high values. The spanloader concept uses payload and fuel distributed along the span to react the airloads. Often on a ground-based spanloader configuration this distribution, while relieving the unbending loads in flight, causes severe penalties due to down bending loads while on the ground. Since the primary wingship flotation is provided by the wing, these down bending loads are reacted by air loads in flight and by flotation loads while the aircraft is in water. In fact, flotation loads are such that the wing does not encounter downbending loads. Another reason for low loads is the maneuver load factor being 1.5g in lieu of the more normal 2.5g. This load factor was lowered for the wingship aircraft because rapid attitude changes are not required when the maximum cruise altitude of approximately five feet (1.52m). Essentially the flight regime is straight and level with skid turns. The 1.5g flight case indicates a root bending moment of about 120 million in-lbs. (13.5 million N-m). The other condition shown represents the worst possible bending moment condition. The aircraft is supported by the end endplates only with the entire payload and fuel concentrated at the centerline. Under -1.5g, the root-bending moment for this condition reaches about 426 million in-lb (48 million N-m). For comparison, the C-5 aircraft design root bending moment is about 260 million in-lb (29 million N-m).

Internal loads produced by these bending moments were estimated. The worst condition shows a maximum cover loading of about 4,800 lb/in (841,000 N/m). The C-5 maximum cover loading is about 50,000 lb/in (8.8 million N/m). This indicates the large wing chord and thickness tend to reduce internal loads to very low levels for this size and configuration wingship. Reference 5 is detailed rationale and plots of loads information.

<u>Structural Concept</u> - Most Lockheed wingship structure is typical aircraft advanced technology structure. Wherever possible the structure is molded advanced composites with selective metallic reinforcement. There are some structural features determined by the configuration or by the specific nature of the wingship aircraft.

<u>Wing</u> - The wing is a large structure which encounters relatively low flight loads. A large penalty, peculiar to the spanloader concept, is incurred by the wing from the heavy vehicular cargo floor. This is estimated to be 10 lb/ft (48 kg/m). The flaps are a simple hinge, split flap arrangement. They are designed to load up to the maximum required hydrodynamic load, and blow back or relieve if maximum allowable water contact speed is exceeded during landing. The underfloor area of the wing is used for fuel tanks, and is compartmentalized and sealed. The sealed compartment concept allows the aircraft to remain afloat after suffering impact damage from floating debris.

The Lockheed wingship endplate structure is designed to react impact loads from the 1/1000 highest wave at cruise speed. The worst condition occurs upon wave impact during a yawed turn. The endplate loads for Seastate 4 conditions are based on a 1/1000 highest wave impact depth of 1.4 ft (0.43 m). Although the endplate structure is designed for the Seastate 4 condition, a much higher load could be tolerated. This implies that a safety margin of about three is incorporated in the design. In reality, this margin reflects the low stress levels used in the design. It was necessary to incorporate low stress levels to account for unknown fatigue and dynamic response problems due to repeated wave impact. However, an impact depth greater than the 4.3 ft (1.3 m) depth could cause the endplate to separate from the wing and possibly cause the loss of the aircraft. It is noted that any wave which impacts the basic wing or fuselage structure at cruise speed would likely down the aircraft, since these structural components are designed to react water impact at speeds no greater than 16 knots (8.2 m/s).

<u>Fuselage</u> - The fuselage is typical aircraft advanced technology structure. It is primarily skin-stringer design with several floor levels installed for cockpit, relief crew facilities and various systems installations. The lower fuselage is used for flotation and is compartmentalized to allow for damage. The fuselage's most unusual feature is the engine mounting arrangement. A continuous torque box spans the fuselage width and supports all four engines. The engines are rotated by actuating the entire torque box and moving the engines as one unit. The fuselage weight is penalized by about 10% to account for the torque box arrangement.

The engine installation is unusual. The engines are cantilevered from the side of the forward fuselage. To account for the higher bending moments, the normal pylon and nacelle weight is doubled. An additional weight penalty of 1,000 lbs (454 kg) has been incorporated into the surface control system to account for the engine rotation actuation system.

A single, V-shaped, retractable hydrofoil was incorporated in the Lockheed wingship design for landing purpose only. The foil had a span of only 15.2 ft and a chord of 7.6 ft. The hydrofoil is extended at 150 ft/sec (89 knots). At 125 ft/sec (74 kts), it develops a maximum lift of 505,000 lbs and a maximum drag of 168,000 lbs. Reference 5 describes the hydrofoil.

Comment: It is apparent that if this wingship was re-examined today in light of the Russian experience, the greatest impact would be on PAR performance. The speed of 16 knots and the associated loads would have to be increased considerably, which in turn, might increase structural and empty weight fractions.

Northrop 1.6M Wingship

An overview of the Northrop Wingship 1.6M is shown in Figure 3-16, taken from unpublished information provided to Carderock Division, Naval Surface Warfare Center (CDNSWC). (Reference 6.) Little Model 1.6 information other than that shown below was available.

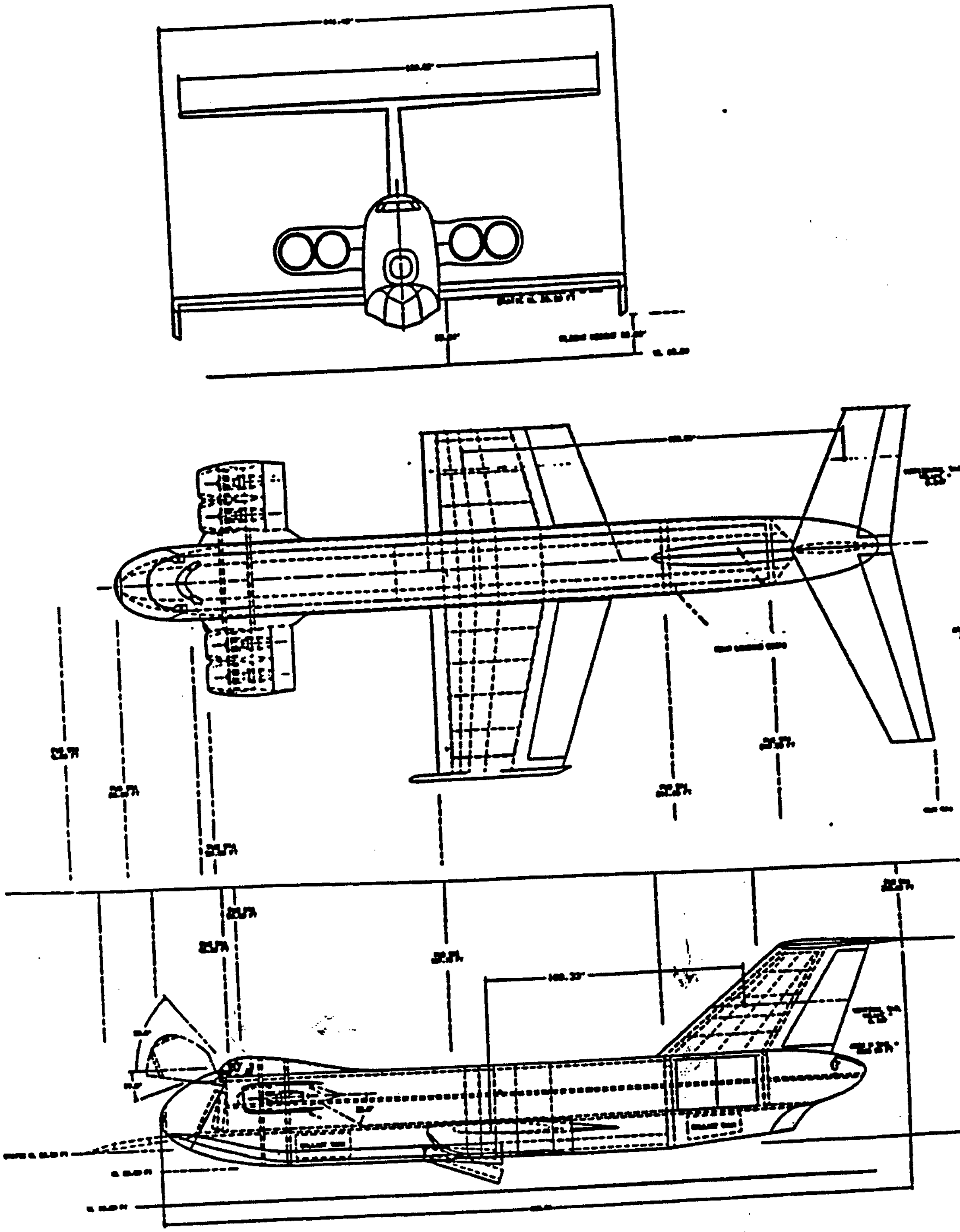


Figure 3-16 - Northrop Wingship 1.6M

Physical characteristics of the Northrop Wingship are summarized as follows:

Dimensions	
Length	282 ft
Height	70 ft
Wing Span	141.4 ft
Wing Root Chord	65ft
Wing Tip Chord	44.7 ft
Wing Area	7,778 ft^2
Wing Thickness Ratio	approx. 8 %
Wing Loading	206 lb/ft^2
Aspect Ratio	2.6
Propulsion Engines (flight)	(4) Fixed pitch Advanced Technology bypass ratio turbo fans, about 84,000 SLS thrust each.
Weights	
Structure	527,836 lbs
Propulsion	158,233 lbs
Weight Empty	751,369 lbs
Operating Weight	762,568 lbs
Payload	320,000 lbs
Fuel Usable	517,432 lbs
Basic Mission Takeoff Gross Weight	1,600,000 lbs

Note that these values indicate a structural weight fraction of 32%, and an empty weight fraction of 47%. Detailed weight breakdown is provided in the Appendix C (Structures).

Douglas Aircraft Wingship (Wingship-S)

An overview of the Douglas Wingship-S is shown in Figure 3-17, taken from Reference 7.

Keep in mind that the Douglas Aircraft Wingship-S vehicle, described in Reference 7 was analyzed without the benefit of the information and knowledge recently received from Russian wingship experts.

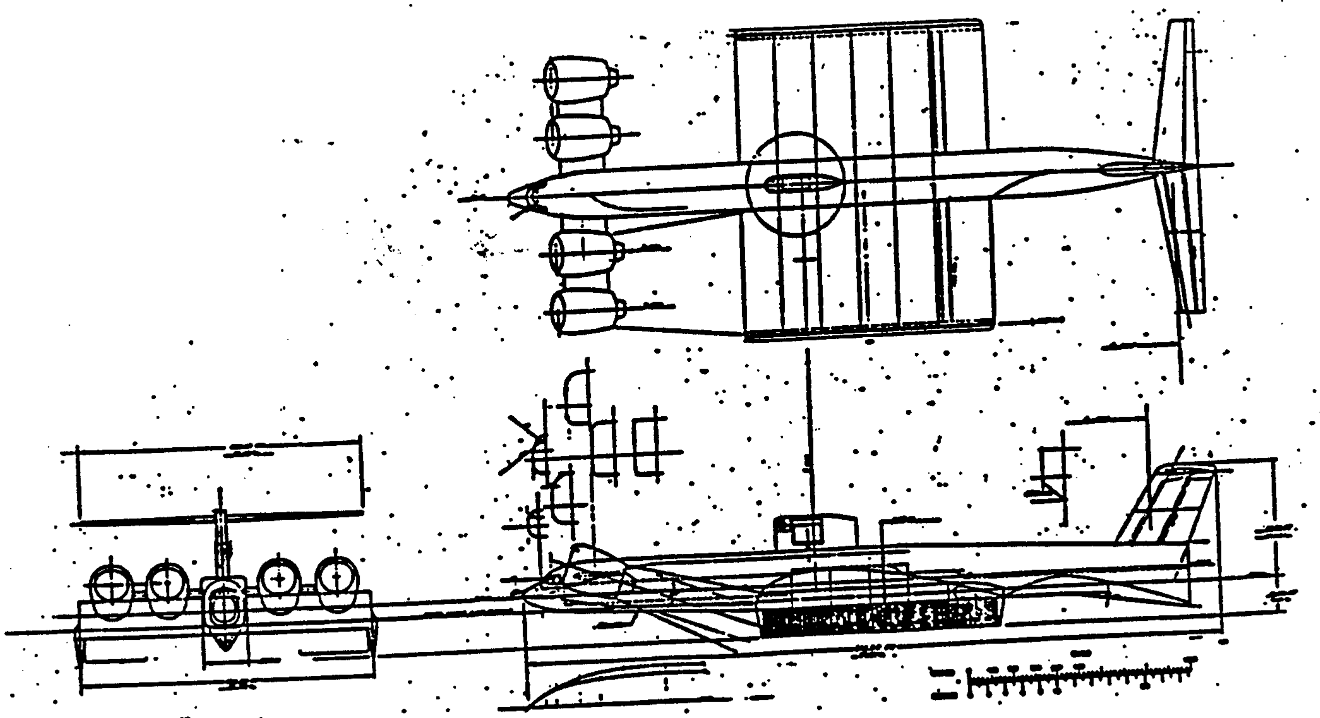


Figure 3-17 - Douglas Aircraft Wingship-S

The 2,000,000-lbs vehicle uses the power augmented ram (PAR) wing concept. The under-wing pressure cavity is energized from the exhaust of the four canard mounted engines. PAR is used at all speeds and the forward engines are fixed at the deflection angle shown. The under-wing pressure is contained by plain flaps on the rear of the wing and a pressurized inflatable skirt extending vertically along the wing tips. The engines are very high bypass ratio turbofans of 95,000 lbs sea level static rating.

According to Reference 7, the Douglas Aircraft Wingship-S takes off and lands vertically at zero forward speed and hydrodynamic forces on the fuselage due to forward motion are not anticipated. The wing is also mounted flush with the bottom of the fuselage to prevent wave impact. The fuselage, therefore, is similar to a conventional landplane design and has no seaplane keel, chines or deadrise contours, and is designed for floating loads only. A substantial ski structure is included under the aft fuselage to assist in vehicle longitudinal trim during takeoff and landing. A conventional "T" tail empennage also maintains trim and stability at forward speeds.

Structural Aspects of Douglas Wingship-S

The 1977 structural design of the Douglas Aircraft Wingship-S vehicle, reported in Reference 7, was based on anticipated 1990 technology capability that emphasized advanced aluminum alloys and tempers, and advanced composite construction. Graphite/epoxy (Gr/Ep), boron/epoxy (B/Ep), and Kevlar/epoxy (Kev/Ep) advanced composite materials were receiving the most attention and were believed to be most likely developed for 1990 technology design.

A production wingship design would make maximum use of emerging new aluminum alloys such as 7049, 7050, and 7475 which have good toughness, crack propagation and stress corrosion properties, as

well as high strength and stiffness. New titanium alloys were considered along with appropriate current alloys.

The major advanced composite application was in the wing and empennage. The main structural boxes, control surfaces, and fairings were primarily composite construction.

Wing - The wing has a rectangular planform and a constant cross section. It consists of a leading edge, main structural box, trailing edge and flap. All fuel is carried in a wing tank extending from the front to rear spar along the entire span to a height of 1.35 m (53 in) above the lower surface. This arrangement minimizes both spanwise and chordwise wing bending and allows upper tank panels to be used as a floor for personnel, equipment, and/or cargo.

The basic structural system consists of five spars, ribs 1.02 m (40 in) on center and stiffened cover panels. Component construction utilizes forms compatible with structural requirements and reliable manufacturing processes. The basic concept is stiffened panel and multi-rib construction. These forms have demonstrated a high level of structural efficiency with good inspectability and repair capability. Minimum sandwich construction was considered because of problems associated with fabrication, inspection and environmental response. The composite components were to be cocured to form large integral structures which are mechanically attached to form complete assemblies. The loading conditions considered were:

- Wing shear and bending under 29 flight loads.
- 107 kPa (15.45 psi) ultimate wave impact pressure on vehicle at rest.
- 152 kPa (22 psi) ultimate internal fuel over-fill pressure.

Comment: Note that these values are much lower than those used by the Russians.

The critical condition for the lower wing panels is the fuel over-fill condition which imposes an equal internal pressure on all sides of the fuel tank.

Empennage - The empennage structural design is similar to the wing. Both horizontal and vertical tails consist of main load carrying boxes (spar/rib/panel configurations) with leading edges, trailing edges and control surfaces attached. The major components are primarily composite stiffened panel and multi-rib construction. Empennage loads are such that a large percentage of box panels and skins are minimum gage structure.

The critical loading conditions are:

- Fuselage shear and bending under 1.25 g while at rest in Seastate 6.
- 180 kPa (26.10 psi) ultimate external wave impact pressure while vehicle is at rest.

Shear and bending was assumed to effect the fuselage shell from the ends to the forward and rear spars respectively, as shown in Reference 7, Figure 2.3-4. Both wing and fuselage are effective in between. This produces maximum axial panel loads at the front and rear spar stations. The upper panels are designed for stability under axial compression. The lower panels are sized for ultimate tensile loads. The same panel depth is used to resist bending from water pressure.

Comment: It is apparent that if this wingship was re-examined today in light of the Russian experience, the most impact would be on PAR performance. The speed of 16 knots and loads associated with same would have to be increased considerably, which in turn, would increase structural and empty weight fractions.

Risk Area Definition

According to the Douglas report, the only risks involved in new or conventional metallic structures are generally those related to new processes. In addition, scaling up from small development articles to full size production components will incur economic uncertainties related to new equipment and process variables.

In 1977 Douglas considered the risks associated with composite elements and components reasonable. The criteria for reasonable risk is that the same, or similar types, of structure should have successfully completed design and development, including static and dynamic ground tests, and have undergone a prescribed period flight testing. Significant composite structure programs (past; current and near future) which would have provided experience related to this effort by 1985, would permit reasonable risk application to complete wing and empennage structure and secondary fuselage structure. Composites were not considered innately less applicable to fuselage shell structure than other parts of an airplane. However, Douglas did not anticipate the projected state of technology to be at a competency level commensurate with reasonable risk by 1985.

Aerocon Dash-1.6

The 5,000-ton wingship design by AEROCON is illustrated in Figure 3-18. (Reference 8.)

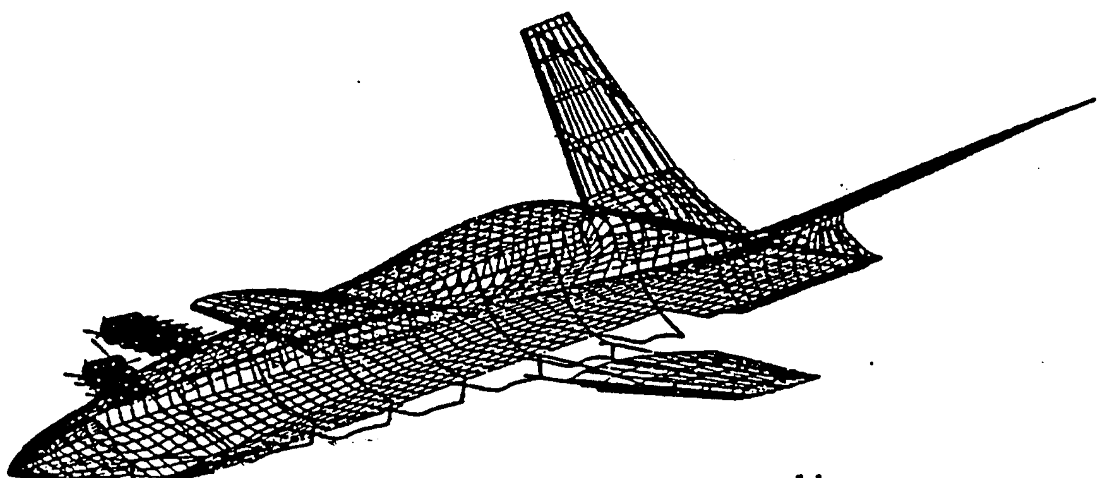


Figure 3-18 - AEROCON 5,000-ton wingship

The AEROCON DASH 1.6 wingship design has the following physical characteristics (Reference 8):

FUSELAGE	
Length (overall)	566 ft
Maximum Height	112 ft
Max Beam (Strake)	116 ft
WING	
Span	340.00 ft
Root Chord	156.00 ft
Tip Chord	60.00 ft
Wing Planform Area	38,720.0 ft^2
Aspect Ratio	3.15
PROPULSION BRIDGE	
Overall Span	236 ft
Root Chord	64 ft
Gross Area	13,087 ft^2
Aspect Ratio	4.25
EMPENNAGE	
Overall Span	320.00 ft
Root Chord	85.00 ft
Tip Chord	33.00
Empennage Planform-Span Area	18,680.0

The AEROCON DASH-1.6 wingship Design has the following performance goals:

Takeoff Gross Weight, WO	5,000 tons
Empty Weight, WE = .3588 WO	1,794 tons
Max Fuel, WF max = .52 WO	2,600 tons
Max Payload, WP max = .345 WO	1,725 tons
Max Payload at WF max	606 tons
Wing Loading	258 lb/ft^2
Takeoff Speed (Based on $C_L = 1.0$)	276 knots
Cruise Velocity, VC	400 knots
Cruise (clearance) Altitude, HC	12 feet
Cruise L/D	32.5

Detailed physical characteristics, estimated performance values and weight breakdown are provided in the Appendix C (Structures).

A unique characteristic of the DASH 1.6 is its land overflight capability. A flight altitude of 6,000 feet and a flight velocity of 400 knots are assumed for assessment of transit over land barriers. The Suez Canal was the example chosen and a sustained free air flight of 500 nautical miles at an altitude no higher than 15,000 feet was selected. The climb estimations are based on small angle unaccelerated climb using the initial cruise speed, full power thrust-to-weight and lift/drag value of 15. During climb, all engines (cruise and PAR) will operate with thrust augmentation (duct burning), and a value of 2.0 for thrust specific fuel consumption (TSFC) is used. During climb and cruise at 6,000 feet, a conservative value of 15 for lift/drag was chosen from the DASH-1.6 drag polar. During cruise at 6,000 feet, a sufficient number of engines (of the total of 16 engines) will be operated to keep the TSFC at 0.6 or less.

Loads Considerations

As originally envisioned by many U.S. researchers, the PAR effect was expected to lift the wingship above the water surface at very low speeds. Thus the hydrodynamic loads during takeoff and wave impact loads during landing were expected to be quite small. In fact, the Lockheed and Douglas designs previously described were based upon this assumption. Unfortunately, Russian experience with full scale wingships contradicts this assumption. The PAR effect did not support the craft at low speed, and the takeoff and landing speeds were very high. For example, the takeoff speed of the LUN is 340 km/hr (which is 65% of the cruise speed) despite activation of the PAR system. Thus, the hydrodynamic loads throughout the takeoff and landing sequence are significant and, indeed, dominate the structural design of the hull, wing, wing flaps, end plates and etc. Recognizing the severity of the landing impact loads, the Russians have incorporated a relatively heavy, retractable, hydroski beneath the hull to reduce impact forces.

In addition to the hydrodynamic loads developed during normal operation of the wingship, possible impact with unusually high waves (so called rouge waves) while flying in ground effect at cruise speed seriously concerns wingships designers. It was reported to WTET that an unidentified Russian wingship struck such a wave at cruise speed, experienced an 8 to 10g impact acceleration and sustained severe damage at the PAR engine mounts. (Reference 4) Although it would be preferable to avoid or preclude such impacts, it may not be practical to do so. In this case, the impact of such loads would have to be considered in a specific design. If, in the judgment of the designers, the result would be unacceptable performance degradation, an up-front risk acknowledgment would have to be made as part of the decision making process (See Item 2 under "Recommended Experimental Studies.)

At present there are few published analytical or experimental data on wingship impact loads and pressures. The Russians did not share their methods with WTET. It was stated however, that the Russians design their vehicles for a 4g acceleration at the center of gravity and then estimate (using empirical formulations) the maximum operational wave height as a function of landing speed and gross weight (Reference 4). Regarding bottom pressures, which design the bottom scantlings, the Russians also reported that the maximum pressure measured on the LUN hydroski was approximately 290 psi. (Reference 4).

In summary, unless the PAR system can be designed to support the wingship at low speed, the designer should be prepared to provide a robust structure capable of sustaining large hydrodynamic impact loads and bottom pressures. This heavy structure will surely compromise the useful load fraction.

Typical Takeoff and Landing Scenarios

At low speed, where buoyant forces are still appreciable, maximum pitch and heave motions are expected.. For seastates where $H_{1/3} > 0.40$ beam, green water may wash over the bow, windshield, wings, flaps and possibly flood the PAR intakes.. The wings and flaps are in contact with solid water and the end plates are submerged.

As speed increases, hull hydrodynamic forces dominate while aerodynamic control remains small. Large spray sheets develop as the hull slams into oncoming waves. The large kinetic energy of the spray can damage wing flaps if they are extended and not designed with load alleviating devices. In the LUN, the wing flaps are deployed only partially in this speed regime to avoid contact with spray.

At speeds nearing takeoff, the hull continuously strikes the oncoming wave train. It develops hull impact loads and pressures which can be significant since the hydroski or other load alleviating devices may not be

deployed during takeoff. The wing end plates are constantly penetrating the oncoming waves and must be designed to withstand large side forces if the vehicle is yawed.

When landing, the vehicle is expected to approach the wave surface at a positive trim angle and finite flight-path angle. Although sufficient aerodynamic capability exists to control the initial touch-down conditions, experience with water-based aircraft has demonstrated that maximum loads and pressures occur in the subsequent run-out where there is insufficient aerodynamic capability to control hull-wave impact conditions.

Current Status of Hydrodynamic Load Technology

Since there are few published analytical methods or experimental data related to hydrodynamic loads on wingships, it is useful to refer to the extensive U.S. experience with water-based aircraft.

The U.S. has relied heavily on model tests to evaluate the hydrodynamic performance of every water-based aircraft design. These experimental studies define such basic waterborne characteristics as: resistance, hump speed, spray envelopes, porpoising limits, lateral stability, impact loads, bottom pressures, etc. In addition, elemental studies define the effect of hull geometry, loading, speed, wave severity and aerodynamic control on each of these hydrodynamic characteristics. Empirical design methods based on regression analysis of these experimental data have been developed.

Analytical studies of the basic landing impact process define impact loads and pressures as a function of assumed hull-wave contact conditions. References 9, 10 and 11 typify many published impact process analytical studies. While providing reasonable results for the initial touchdown condition, they require knowledge of the random combinations of speed, flight path angle, hull trim and wave shape which occur during the run-out where the impact loads are maximum. Time history solutions of the run-out process must be developed to quantify motions and accelerations associated with landings in irregular seas. Existing time-dependent solutions (especially for planing craft) have met with some success in describing hull motions, but seriously miscalculated impact accelerations. Continued development of these analytical methods is essential but, lost support when the U.S. Navy terminated their interest in water-based aircraft.

In any event, analytical results must agree with experimental data to establish credibility. Thus while model tests are the preferred method for determining design loads, analytical studies should also be pursed. Empirical methods for estimating the impact loads for water-based aircraft landing in irregular seas have been developed based upon numerous model test results. Reference 1 (Section 5.4.4.4) elaborates on the theoretical aspects of this problem. Therein, the impact acceleration increases linearly with hull beam. Since a hydroski has a smaller beam than the hull, it is expected to reduce impact accelerations. This validates the use of hydroskis on Russian Ekranoplans.

Although existing seaplane design procedures offer some guidance in estimating design loads for wingships, they may not be directly applicable because of the unique features of the wingship. For example:

(a) The wingship wings are close hull's bottom and provide lateral stability while at rest. Thus, they are vulnerable to wave impact.
(b) The aerodynamic ground effect on the wing will provide a "cushioning" action during landing.
(c) The high velocity air stream from the PAR system will interact with the wing to produce additional aerodynamic forces which will influence the hull trajectories in waves.

(d) The proximity of the deflected wing flaps on the low wing to the water surface will subject them to large loads due to impact with green water and high energy spray sheets developed by the hull, PAR and end plates.
(e) The wing end plates may be partially submerged throughout the operation and will develop large drag and side forces in the yawed condition.

Construction Materials

A discussion of construction materials based on large Soviet wingship experience from Reference 2 is found in the Appendix C (Structures). This should provide a departure point for material considerations of any large wingships U.S. anticipate building.

Structural Weight And Empty Weight Fractions

As an example of the wide diversity of empty weight and structural weight estimates for various "designed" large wingships, the following table is provided.

STRUCTURAL WEIGHT AND EMPTY WEIGHT SUMMARY

Vehicle	W Tons	Structural Weight Fraction (%)	Empty Weight Fraction (%)
ORLAN	110	34	50
LUN	400	34	50
Lockheed	681	16	26
Northrop	800	32	47
Douglas	1000	12.5	25
AEROCON	5000	20.7	33.7

A major design requirement for large wingships is that the large differences between projected and achievable weights, both structural and empty weights, must be completely understood.

3.1.3.3 Preferred Technologies

For the 400-ton, 1,000-, 2,300- and 5,000-ton wingship alternatives, priority is placed on advanced high strength lightweight materials and structural design methods. Large wingship structures require advanced aluminum, titanium, composites materials or a combination of them.

Modern composites with imbedded boron (expensive), carbon, graphite and Kevlar fibers have significant weight savings over conventional aluminum (about 25% to 30%). Cost increases associated with composites could be dissipated with increased emphasis on reducing structural pieces, component commonality and structural simplification. Modern composite matrix materials such as thermoplastics, metals and polyimides could lead to even lighter wingship structures.

Substantial analysis and testing is required to use advanced composites technologies for wingships. Unlike metals, the strength and stiffness of advanced composites can be tailored to meet load requirements. Research and development is critical to prevent problems from environmental heat and moisture, fatigue and slamming damage, and delamination failure.

Some composites are poor energy absorbers, therefore, wingship slamming loads and their effects needs to be studied thoroughly.

For 400-ton, and perhaps the 1,000-ton, wingships a primary aluminum structure may be the optimum structure with secondary structure of advanced composites. Most likely, the 2,300-ton and 5,000-ton wingships need a primary structure of advanced composites. Some factors affecting the final determination of composite laminates are mechanical properties, ease of manufacture, heat resistance, cost, delamination resistance, fatigue resistance, and toughness. For the 2,300 ton and 5,000 ton wingships using sandwich core material in the fuselage, wings and appendages may be the best option. Sandwich structures generally have high stiffness to weight ratios. Two of the best cores are honeycomb and foam.

3.1.3.4 Deficiencies

One of the major deficiencies designing the 400-, 1,000-, 2,300- and 5,000-ton wingships is a complete understanding of hull pressures from slamming loads. Water-based aircraft analytical methods and data may provide a point of departure. However, as wingship size increases, it becomes more important to know and understand these pressures with great precision. Von Karman and Wagner have tested aircraft slam pressures. Generally, they found that the pressure varies with forward speed, trim angle and deadrise angle of the craft. Although these empirical equations are sufficient for smaller craft, the equations may be too simplistic and entirely inaccurate for large WIGs. For example, in ship structures the relative stiffness of the impacted panel is essential to calculate slam pressures. None of these simplistic approaches considers vehicle stiffness among other factors. Generally, if the natural frequency of the panel and the frequency of the slam loads are similar, the impact pressures and response are greater.

Developing the optimum composite materials with added materials such as boron involves an advancement on the state of the art with these materials. The overall cost of the wingship structure is highly dependent on the manufacturing process used for the composites structures.

The U.S. Navy has used the Resin Transfer Molding (RTM) process to manufacture high quality, low cost composite ship hulls and secondary structures. The composite wingship components have different fatigue and fracture characteristics than conventional metal structures and this needs to be studied. The environmental effects on the material would require development. The normal WIG operating loads requires model testing and analysis. For instance, in the normal operating model how often would the wingship strike a wave and what would be the magnitude of these loads? For the 5,000-ton wingship the slamming and operating loads require far more testing than for smaller wingships.

See discussion of "Risk Areas" under the 1,000 ton Douglas wingship design summary in Section xxx

3.1.3.5 Development Required

The tasks outlined below apply to large Wingships in the 400-ton through 5,000-ton categories.

1. Review past designs for structural characteristics
2. Materials assessment
3. Experimental and analytical determination of operating and slam loads (See below for detailed recommendations.)
4. Preliminary structural design
5. Build coarse element Finite Element Model (FEM) of craft and conduct FEM analysis for operating and slam loads. Provide inputs to wingship designs

6. Design and build scale models of operating craft and perform tests at sea (measure loads and slam pressures, structural response)
7. Design and build component models of craft (panels, wing, fuselage) and perform static, fatigue, fracture, and tests
8. Design and build models of connections (mechanical fastening, adhesive bonding, thermoplastic welding) and perform fatigue tests
9. Build finer mesh finite element models of craft components
10. Redesign craft structure based analysis and testing

Create a program in the structures area which does several things:

(A) Identifies the needed properties of the composite, including honeycombs and coordinates these with the materials end of the AIR 05 organization in NAVAIR. Producibility of very large composite parts, typical of big wingships, is to be one of the needs to be fleshed out.

(B) A computational procedure that uses finite element analysis to size and weigh parts, particularly composites, and links this information to producibility decisions is vital and must be developed since no one in the U.S. has build a large wingship. This capability will be needed before Demonstration/Evaluation (6.3) can be started on structures. The effort will be to demonstrate that large parts built from the CAD/CAM finite element/producibility computational capability indeed weight what has been predicted and have the predicted strength. Having done this, the capability may be considered "validated" and ready for engineering development application on a full scale wingship.

(C) Build and destructively test large composite parts of:

Fuselage/hull mid-section

Wing sections

Carry-through section

(D) Validate computer programs from above tests

Recommended Experimental Studies

1. Overview Tests:

Construct a scaled dynamic model of the Russian LUN or new 400-ton wingship design with the capability of adjusting the wing's vertical location, incidence and aspect ratio. Provide a retractable hydroski attached to the hull; install a PAR system which can be deactivated; and install wing flaps with adjustable deflection angles.

Select a model size, loading and test conditions which will enable test results to be scaled to wingship sizes up to 5,000 tons.

Conduct takeoff tests in various irregular seastates for parametric variations in wing geometry, vertical location and flap deflection angles. Test with and without the PAR system, and with and without the hydroski attached.

Conduct landing tests in irregular seas for the same parametric variations as in the takeoff tests.

Conduct sea-sitting tests to establish motion characteristics of the 400-ton wingship design.

Conduct all tests for a range of constant speeds and some at constant thrust (free-to-surge) and measure the following quantities:

(a) Drag (average)
(b) PAR thrust
(c) Hull trim and heave time histories
(d) Impact accelerations at CG, bow, and stern
(e) Impact pressures and bottom loads as a function of unsupported panel area
(f) Hydrodynamic loads on flap
(g) Spray envelope
(i) Wave spectrum Motions at zero and low speed comparable to a loiter mode.
(j) Provide TV coverage from several angles
(k) Other miscellaneous measurements

In these initial tests the model will be constructed to provide rigid body measurements. These can be used as inputs to an analytical hydro-elastic study of the loads on the full scale vehicle.

This series of "overview" tests will also provide the guidance to develop suitable elemental studies of separate vehicle components to understand better the processes involved in generating hydrodynamic loads.

2. Tests of End Plates:

Mount the end plates on a separate dynamometer and measure the drag and side force as a function of speed, yaw angle and immersion depth. (Tests described by Barkley, Reference 12.)

3. Effect of Hull Geometry on Impact Loads:

Conduct landing impact tests on various hull geometries (including double chine hull form) to identify hull shapes which reduce impact loads and are still functional. The objective is to develop a hull form which may replace the heavy retractable hydroski. This is an elemental study using the hull alone as the test model and should be integrated with mission-oriented design study.

4. Influence of Ground Effect on Impact Loads:

Conduct hull impact tests with and without simulated ground effect to evaluate the significance of this effect on the impact process.

5. The results from all these tests will be compared with seaplane predictive procedures to define the extent of application of these methods to wingships.

Recommended Analytical Studies

An analytical wingship behavior model in irregular waves is a complex problem. It must represent different types of fluid phenomena including aerodynamic, hydrodynamic, hydrostatic, impact and time dependent coefficients which become discontinuous when the vehicle flies off a wave crest to impact against the oncoming wave trough. In addition, the wave profile is constantly changing. Several attempts have been

made to develop a seaplane program with varying degrees of success. The Beriev Design Bureau in Russia stated they are in the process of developing such a program.

Analytical models of high speed planing craft operating in regular and irregular waves (References 13 and 14) are successful in predicting hull trajectories but underestimated the impact accelerations and do not consider bottom pressures. Reference 15 presents the results of an experimental and analytical study defining amplitude and frequency dependence of the restoring forces, damping and added mass associated with a vertically oscillating deadrise surface. Significant non-linear effects were identified in the restoring force and relatively smaller ones in the damping and added mass terms. Perhaps some of these approaches and results can be applied to a wingship landing simulator when aerodynamics and ground effect are incorporated.. Computer-based analytical models need to be developed, verified and made available to the wingship design community.

3.1.3.6 Cost And Schedule

400-ton wingship Tasks 1-10 above , experimental and analyitical studies
3 years at $16 million/year
Total $48 million

1,000-ton wingship Tasks 1-10 above
5 years at $18 million/year
Total $144 million

2,300-ton wingship Tasks 1-10 above
8 years at $18 million/year
Total $144 million

5,000-ton wingship Tasks 1-10 above
10 years at $20 million/year
Total $200 million

3.2.1 Sensors and Navigation

Sensors and navigation systems for wingships will be unique combinations of existing sensor types. Some development may be required to support the design of the wingship, but these technologies do not have much potential to improve the overall vehicle performance.

3.2.1.1 Requirements

Two factors drive the wingship's requirement for special sensors. These are its proximity to the water in cruising flight, and the rough and unpredictable nature of the water's surface. We treat the latter at some length, then discuss flight altitudes and finally proceed to instrument needs.

Seastate

The configuration of the ocean's surface is best described as consisting of multiple waves having a Gaussian (normal) distribution of amplitudes and also a related frequency spectrum. The distribution, or probability density of wave heights, H (crest to trough), is given by the Rayleigh function $p(H) = 2H/E \times \exp\{-H^2/E\}$, where E is related to the total energy in the waves. The integral over H from 0 to infinity is unity. The wave spectrum depends upon the frequency spectrum amplitude $A(\sigma)$ through E, which is the integral over all frequencies of the square of A.

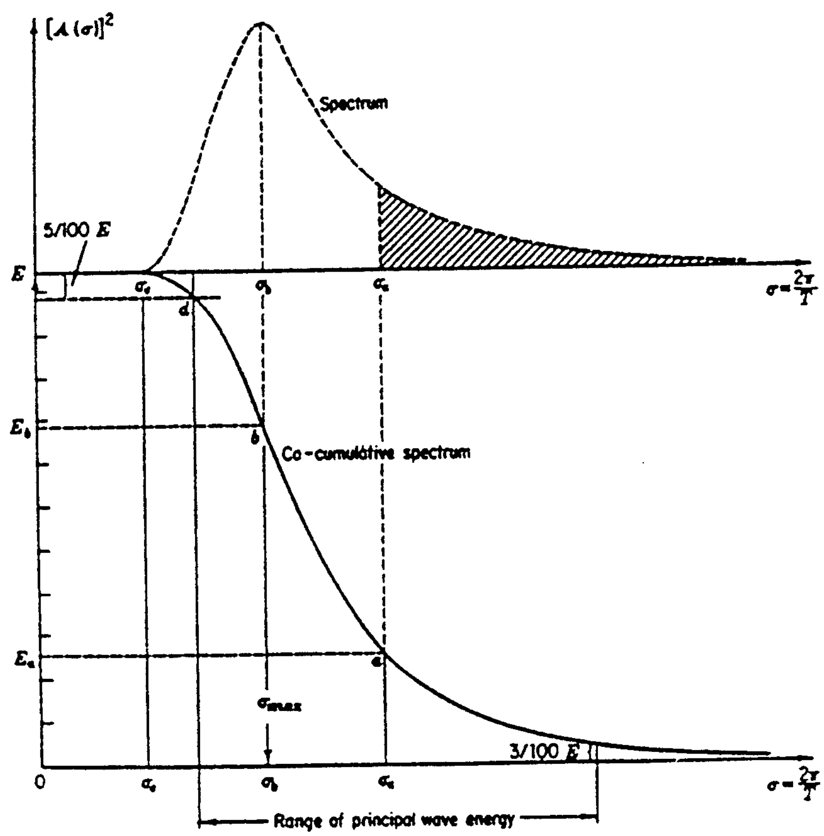


Figure 3-19 – Frequency spectrum and integral (Reference A.1)

Figure 3-19 (Reference A.1) shows a frequency spectrum and its integral. The spectrum depends on windspeed, duration of time that the wind has blown, and fetch, i.e., the distance over which the wind acts. A fully aroused sea is in equilibrium with the steady wind, not limited by fetch or duration. (The mathematical material is taken from Reference A.1 and the more applied material from Reference A.2. Reference A.2 is universally known as Bowditch. It was first published in 1802.) Given wind speed, fetch, and duration and the frequency spectrum has nearly zero amplitude below a critical frequency, σ_c radians/sec. That is, only $\sigma > \sigma_c$ contribute to the energy in the waves. With greater wind speed, fetch or duration, Amplitude ($A(\sigma)$)gets larger and moves to lower frequencies. Let U denote windspeed in knots. Then the frequency of maximum spectral amplitude is $f_{max} = 2.48/U$, about twice the critical frequency; the amplitude A scales as U^{2n} with n between 2 and 2.5 depending upon which theory and data are used.

Figure 3-20, from (Reference A.1), shows the quantity $E(f)$, which is the integral of the squared amplitude of the frequency spectrum from $\sigma(=2\pi f)$ to infinity. The quantity E is related to energy and $E/2$ equals the variance of the Gaussian distribution of amplitudes, and in this formulation scales as U^5. The other lines on Figure 3-20 are the fetch and wind duration limits to E_f.

Various statistical measures of H are used; *e.g.*, the significant waveheight is the average of the highest one-third of the waves and is denoted $H_{1/3} = 2.83 \times E^{0.5}$. Similarly $H_{1/10}$ is the average of the highest one-tenth of the waves. The significant wave height of a fully aroused sea varies with U^n where n is between 2 and 2.5. Using the numerical values in Figure 3-20 we find that $H_{1/3} = 4.4 \times 10^{-3}\ U^{2.5}$.

Wavelength and speed in deep water relate to frequency approximately as follows:

$$S[\text{knots}] = 3.03 \times T = 3.03/f,$$

where $T = 1/f$ is the wave period in seconds, and wavelength, L, is given by

$$L[\text{feet}] = 5.12 \times T^2.$$

Thus $S = 1.339\ L^{0.5}$.

(Hence hull speed of a ship is proportional to the square root of boat length, obtained by setting length proportional to the wavelength of the wake.) We can also calculate the wavelength associated with f_{max} as $L_{max} = 0.835\ U^2$. As examples see Table 3-4. However, this wavelength is not strictly associated with the highest waves. All of these descriptions are statistical. An additional rule of thumb is that breaking of crests limits the ratio of wave height/length to less than 1/7.

Wind, U [kt]	$H_{1/3}$ [ft]	f_{max} [1/sec]	L_{max} [ft]
20	8.5	0.12	355
28	18.3	0.088	654

Table 3-4 - Some parameters versus windspeed.

Waveheights	Relative Heights
Average	0.64
Significant (highest 1/3rd)	1.00
Highest 10%	1.29
Highest 3%	1.54
Highest 0.1%	1.94

Table 3-5 - Relationship of different wave heights.

Wind, knots	Significant Waveheight, m	Seastate Code
< 1	0 Calm/glassy	0
1 - 3		
4 - 6	0 - 0.1 Calm/rippled	1
7 - 10	0.1 - 0.5 Smooth/wavelets	2
11 - 16	0.5 - 1.25 Slight	3
17 - 21	1.25 - 2.5 Moderate	4
22 - 27	2.5 - 4.0 Rough	5
27 - 47 (in 3 ranges)	4 - 6 Very rough	6

Table 3-6 — Relationship of Wind to Seastate and $H_{1/3}$.

The formalism outlined above leads to relationships characterizing wave height contained in Table 3-5, and also to the relationship between windforce and significant waveheight in Table 3-6, (from Bowditch, p 827 and p 1312). The data in Table 3-6 are for a fully aroused sea, and we emphasize are statistical averages. The actual character of the sea depends on the present wind. This data, however, is probably sufficient to both define requirements for detecting seastate and the performance by wingships.

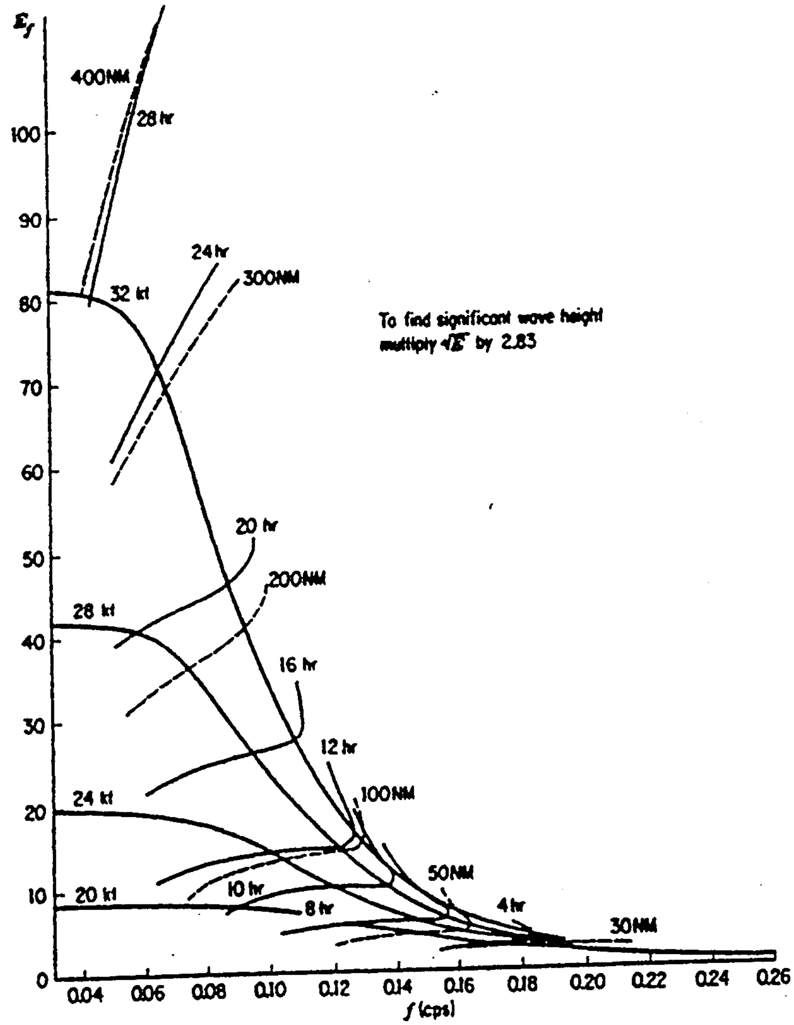


Figure 3-20 - Example of combined duration and fetch graph for co-cumulative spectra. (Reference A.1) The vertical scale has units of ft^2.

Cruising Altitude

Refer to Paragraph 5.4.4.5 of the Wingship Investigation Final Report. A moderately conservative expression for safe cruising height, h, is given by Victor Sokolov, General Director of Central Hydrofoil Design Bureau (TsAGI) as

$$h = H_{3\%}/2 + 0.1\ c$$

where $H_{3\%}$ = 1.54 $H_{1/3}$, and c is the wing chord, which is about 40 feet for LUN. Wave height is measured trough to crest; thence h must be measured above the mean surface, and the formula gives a clearance of 4 ft above the crests of the 3% highest waves. In Seastate 5 with $H_{1/3}$ = 13 ft (4 m), h = 14ft, and the clearance becomes 1.4 ft above the 0.1% highest waves whose crests are 12.5 ft above the mean.

In the case of waves with $L >>$ length of the wingship, the aircraft could fly up and down the wave slopes. Thus the meaning of cruising height depends somewhat upon the selected control algorithm and how it adapts to seastate.

Instrument Needs

Table 3-7 lists the types of measurements, and identifies those that are unique to the wingship. We do not list all engine instruments (*e.g.* torque, rpm, TIT, oil pressure) or system instruments (*e.g.*, hydraulic pressure, generator output, fuel quantity) not unique to wingships. Wingships have the same requirements as other aircraft operating at low altitudes plus the special needs for accurate height and attitude measurements with respect to the water surface. We must decide whether wingships will fly IFR; assume for now that they must. The maximum seastate (roughness) is also not settled; we are assuming State 5.

From consideration of the above we conclude that three unique measurements are needed:

1. Attitude
   Highly accurate attitude;
2. Altitude/Height and Seastate
   Highly accurate height above the surface, with the closely related measurement of seastate;
3. Engine Salt
   Measurement of salt deposited in the engines.

Some additional considerations are:

In arctic waters sea spray can freeze to the aircraft structure when the air is cold enough. This would drastically affect the airflow and weight, and would be a particular problem for exposed sensors such as pilot/static orifices, angle of attack vanes and etc. For operation at high latitudes the aircraft must carry heavy de-icing equipment.

Extra control surfaces unique to wingships and any rotatable thrust line of PAR engines requires mechanical position indicators, but these are not any special new type. The low altitude prevents effective use of VHF navigation signals, but these are not usable at sea even at high altitudes. A combination of inertial navigation and GPS will meet navigational needs as it does for current transport aircraft. Similarly GPS is now usable for terminal navigation. Communication must comprise a combination of high frequency (HF) and satellite link. The practices of surface ships should suffice.

3.2.1.2 Specific Measurement Requirements

Measurement	Uniqueness
PRIMARY FLIGHT Speed Air Water Altitude/height Heading	Unique, but is it necessary? More accurate than standard
FLIGHT CONTROL Attitude Rate of turn Rate of climb Acceleration Hull draft	More accurate than standard Low rates Low Rates Unique, but is it necessary? Include strikes Possibly
ENGINES Engine performance Water/salt ingestion	Unique
NAVIGATION Position Direction to way-points	Limited line-of-sight: Hence no VHF; use GPS
EXTERNAL ENVIRONMENT Terraine Seastate Obstacles	Unique: most critical for Wingship
Water Temperature Depth Salinity	Unique, but is it necessary? " "
Air Visibility Water droplets Temperature Wind/turbulence	Unique
Icing Potential from air Actual on airframe/engine inlets	
FORECASTS Weather Seastate	Unique; no sensor needed.

Table 3-7 - Wingship sensors and uniqueness.

The next sections list each measurement identified as unique, and summarize the requirements. Section 3.2.1.3 describes present sensors for each measurement, their present status and deficiencies.

Altitude and Height

Height above the sea is the most critical measurement. We assume that the wingship span is ~150 ft and that it flies according to the formulation described above. The craft must operate from calm to Seastates 4 to 5 with significant waveheights, $H_{1/3}$ as follows:

Seastate 4	1.5-2.5 m
Seastate 5	2.5-4.0 m

The criterion gives clearance of 4 ft above the $H_{3\%}$ wave crest. Note from Table 3-5 the relationship of $H_{1/3}$ to maximum height. The operating height will range 4 to 14 ft above the mean, and a resolution of at least 1 ft is needed. Pilot or autopilot response drives the sampling interval; we estimate 0.02 sec is needed.

If the wingship leaves ground effect it may fly to a few thousand feet. An ordinary aircraft altimeter will suffice in this condition.

Attitude

Attitude is closely connected with height as it is necessary to avoid catching a wing during a turn and because both the attitude and height sensors couple to the autopilot. As an example, a Lockheed wingship design is expected to survive if an endplate dug into water 1.5 ft, but 4 ft would destroy it. At a height of 4 ft above a maximum wave, a roll of 3° puts the wingtip into water, and this determines roll resolution, which we set at 10% of this minimum amount, or 0.3°. Lower altitudes require closer control of roll. Control of pitch may not be so critical, but the same precision and sampling rate are needed.

Seastate

Safe operation requires determination of the seastate under the aircraft to serve as a predictor of state ahead. Continuous measurement of height above the water with resolution of 1 ft allows determination from the second moment of the variation while the first moment provides height above mean water. A cruising speed of 200 kt = 338 ft/sec. A sampling rate of 50/sec measures all but the shortest waves; averaging must be done over several seconds to encompass the longer wavelengths. The state will not change discontinuously in the open ocean, so measurement over the last 10 miles of track provides the expectation for the next 10 miles. An exception is near the coast or in crossing the boundary between ocean currents.

When such measurements are combined with forecast winds and seas, the statistically expected operating conditions can be predicted some minutes ahead.

Obstacles

To determine how far ahead obstacles must be detected, consider that the wingship can climb 10ft/sec after a delay of ~5 sec between sensing and climbing. Thus climbing to climb 50 ft to clear a small obstacle requires 10 sec total during which the craft will move 3,380 feet at 200 kt. Climbing to 200 ft over a large ship or island will require 25 sec corresponding to 8,440 feet. Distance to the horizon also imposes a constraint. At 6.5 ft above the sea the horizon is ~16,000 feet distant; at 20 ft it is 29,000 ft.

Potential obstacles needing detection include: extra high waves (0.1% waves in Seastate 5, and "rogue waves" completely outside the statistical distribution); stationary obstacles such as islands and reefs;

moving obstacles such as icebergs, seabirds and other natural objects, ships, aircraft and other man-made objects; and intermittent oostacles such as breaching whales. Islands, large icebergs and large man-made objects can be detected by standard radar techniques. Smaller objects, not extending a substantial distance above the mean sea surface, are much harder to discern against the background of sea clutter. Detection of reefs might be important if the reef produces large breakers or if the wingship needs to make an emergency water landing. Intermittent obstacles are a more difficult problem. A breaching whale can enter the flight path of the wingship on time scales of a few seconds. For example, spinner dolphins can jump 20 ft out of the water. Humpback whales (typical length, 45 ft) can propel themselves completely out of the water, not necessarily vertically, to heights of 20 ft or more (Reference A.3). The sizes and altitudes of the cetaceans would enable detection, but wingship operation could be threatened if the breach is too near for response. Like birdstrikes near airports, there are non-avoidable strikes. As wingships must be very strong to withstand water takeoff and landing, they should tolerate strikes with larger objects than a normal aircraft can.

Salt Ingestion by Engines

Ocean salt from spray and droplets will deposit inside the engines, and must be washed out with fresh water after flight. A set of internal probes to measure the deposits might facilitate this procedure. The detectors could be read out after flight.

Forecast Seastate

Both military and commercial organizations provide forecast seastates together with weather predictions. No special equipment is needed to receive the enhanced predictions.

3.2.1.3 State of the Art and Technical Deficiencies

Attitude

We have examined inertial sensors, differential GPS, differential altimeters, and electric field sensors. A general reference is Reference B.1.

Inertial

There are many types of inertial sensors. These can be categorized as rate sensors and attitude sensors. By integration, angular rate measurements can be converted to attitude, and linear (acceleration) to position. Rate sensors, in general, have an internally set zero and need no external reference. The zero and the resolution are subject to bias drift (zero point drift), scale factor variation, and random walk noise. Position and attitude sensors require an external reference to zero them. For example, a directional gyro is set against the magnetic compass, an artificial horizon erects using the local gravitational vertical, and an inertial navigation system requires that the coordinates of the starting point be inserted. The gyrocompass is an exception — it finds true north by sensing the direction of the earth's rotation axis.

The mechanical spinning gyro has a long history in aviation. Variants include vibrating systems. While these continue to find use because they are relatively inexpensive, they do not have the long life or the precision of the best optical sensors. For wingships we do not consider mechanical gyros further. Mechanical (linear) accelerometers will continue to be used; bias residuals are on the order of 12 μg with a 10 μrad alignment residual, and random walk ~0.0005 fps/hr$^{0.5}$. (Numbers are for a QA2000 accelerometer installed in a Honeywell F3 system, (Reference B.2)

Property	Value
Max Input Rate	15°/sec
Bias Stabilty	2°/hr
Scale Factor Error	500 ppm
Random	$0.05°/hr^{0.5}$
Bandwidth	500 Hz
Resolution	1 arc sec
Axis Alignment	300 µrad
MTBF	250 K hrs
Operating Life	> 100 K hrs

Table 3-8 - Honeywell AHRS Fiber Optic Gyro

Optical sensors very actively being developed and are currently used in both military and commercial aircraft. Passive systems include Fiber Optic Gyros (FOG) both resonant and interferomentric. Drift rate of the former has been in the 10°/hr range and the latter are reported as improving into the 1°/hr range (Reference B.3). These devices are adequate for attitude and heading reference systems (AHRS), but are not inertial grade, which requires bias drift < 0.01°/hr in order to be useful for inertial navigation. Table 3-9 is the performance specifications of an environmentally qualified Honeywell AHRS Grade FOG, now available for purchase. As another example, the Collins AHS-85 is an available strapdown system with accelemeters and a magnetic heading sensor that is suitable for attitude and heading control.

Quantity	GG1342	GG1320
Bias stability	≤.002°/hr	.001-.01°/hr
Scale factor stability	3 ppm*	<1 ppm
Axis alignment		<1 arc sec
Random walk	$\leq 0.003°/hr^{0.5}$	$.003\text{-}.01°/hr^{0.5}$
Max rate		1000°/sec

*Assumed error budget.

Table 3-9 — Ring Laser Gyro Performance

Ring Laser Gyros (RLG) are the most stable and accurate systems available, and are widely used for inertial navigation in conjunction with high grade accelerometers. The GG1342 is a Honeywell strapdown RLG with performance shown in Table 3-8. When coupled with a QA2000 accelerometer set and suitable systems it provides inertial navigation with uncertainties ~0.2 nm/hr Reference B.2. Reference B.4 reports adapting a Honeywell GG1320 RLG for pointing and stabilization of aircraft or subsystems (*e.g.*, SAR or IR sensors). He reports the results in shown in Table 3-9. Predictions indicate that this sensor would have

MTBF > 100,000 hrs. Whatever the correct number, we can suppose that it is greater than many other parts.

Like mechanical gyros, optical systems require alignment with an absolute reference at initiation. Some of the latest aircraft use RLG as the prime attitude and navigation reference with the less expensive FOG as a backup and AHRS.

Differential GPS

This technique was demonstrated with multiple antennas on a DC-3 by Graas and Braasch [1991] at Ohio State University (Reference B.5). Ramp tests indicate noise in the 0.1 mrad (20 arc sec) range while flight test data appear to track the real attitude adequately. Aircraft flexing is a major factor. During these tests the receivers locked on three or more GPS satellites.

Differential Altimetry

Differential radar altimetry gives the most accurate reference with respect to the ocean surface and can be combined with altimetry and obstacle seeking, as noted below. In this case a radar transceiver and antenna would mount under each wingtip, and the nose and tail. Suitable averaging and differencing gives both attitude and mean height.

Electric Field

Electric field sensors were developed by Maynard Hill at Johns Hopkins University Applied Physics Laboratory (Refermce B.6) and work very well provided the geo-electric field is vertical along the flight path. The fair weather field is indeed about 300 V/m vertically downward near the surface. (The potential of several 100 kV between ionosphere and earth is maintained by thunderstorms.) According to discussions with Hill and others, the field is irregular near thunderstorms or irregular terrain. Hill thinks this is a good technique for RPV's, but not suitable for operational manned vehicles. According to Professor Robert Holzworth at the University of Washington, who researches atmospheric electricity, the field over the ocean may be confused in the mixed layer (below 1 km altitude) on a scale size of several meters, and may even reverse due to the presence of ions. On the basis of the above we reject this detector for wingships.

Altitude

A pressure altimeter will suffice for flight out of ground effect. Such a standard sensitive (Kollsman) altimeter has resolution and stability of order ±20 ft, not counting the barometric pressure variation. It is not adequate for control in ground effect.

A radar or lidar altimeter is needed for absolute reference close to the sea. We considered visible and infra red (IR) sensors in the 10 μm band, avoiding atmospheric absorption. These suffer from interference by sunlight, scattering and absorption in fog, and poor reflection from the water surface. More investigation of these techniques may be in order.

A standard aircraft radar altimeter operates in the 4.2 - 4.4 GHz range (7 cm) and produces a broad beam, up to 90° depending on the antenna. Several companies make these including Texas Instruments, Collins and Honeywell. Height ranges are zero to several hundred feet with resolution of a few feet. For example, the Collins LRA-900 measures from -20 to +500 ft with a resolution of ±1 st or 2% of indicated altitude, whichever is greater. It is certified for air transport use.

A report from DTNSRDC (Reference C.2.a) describes six years' tests on a Navy hydrofoil. A French unit, TRT AHV-6 modified by Sundstrand, was used initially; later a TRT AHV020 was tested. These units were operated for ~4000 hrs under all conditions including weather up to Seastate 5, icing and weapons firing. No failures occurred; the predicted MTBF for these units is 4,000 hrs. This report gives numerical results only in a plot; resolution and noise appear to be < 1 ft.

Obstacle Detection

Grazing Angle Radar

The need to operate at night and/or in low visibility precludes visible systems, while the presence of water vapor severely limits IR. Radar is the apparent best choice. An obstacle sensor must overcome two major difficulties. First, the horizon is close although large objects will tend to have strong radar return and protrude above the horizon. Second, the rough sea produces a noisy backscatter, generally called sea clutter.

The problem detecting objects against the background of sea clutter in the radar return has been studied for decades and is an active research area (References C.2.b, C.3.b, C.3.6). Understanding of the distribution function of the clutter is needed in order to predict the target detection performance of the radar system and to develop accurate false alarm algorithms. The K-spectrum successfully models the return in many cases (References C.4.a, C.4.b, C.4.c, C.4.d and C.4.3). Many measurements have been made with varying polarization from ~160 to 9000 MHz. The parameters of the distribution are, in part, determined by the seastate, and the wind speed and duration. The radar clutter depends on the presence of whitecaps, and whether the sea is rising, fully aroused or dying. Look angle (up, down, or cross wind; up, down or cross swell) also affects the return through temporal and spatial correlations. At low incidence angles, such as the wingship radar system must use, seastate, shadowing and atmospheric effects are stronger.

The effects of these parameters depends, naturally, on the details of the radar system. Field programs, supported by modeling, have produced sufficient data that a careful analysis should determine a preliminary design for an obstacle-detecting wingship radar. Investigated physical aspects include frequency, frequency agility, Doppler capabilities, polarization, coherence, incidence angle, seastate, wind and breaking waves. In processing algorithms, the use of fractal dimension to discriminate between clutter and clutter plus target shows promise (References C.6.a, C.6.b) , as does using higher order statistics beyond the mean and variance (Reference C.5). Proper choice of the clutter distribution function is necessary to control the false alarm rate. While much work has been directed toward detecting targets, some work has successfully identified "sea spikes" in the return with breaking waves (Reference C.3.a). This may hold promise for identifying very large waves.

Millimeter Waves

Substantial effort has been directed towards using radar to provide terrain following capability. In some cases a radar works with a digitally stored topographic map. The radar updates the position of the aircraft over the land and the system provides visual inputs to the pilot. Obviously a map is not relevant at sea. However, the radar portion of such a system may be useful. Honeywell [private communications Zelenka (NASA/Ames) and J. Hagar (Honeywell Military Avionics), August 1994] have developed a system for helicopter terrain avoidance starting with their 4.3 GHz radar altimeter. To provide a narrow beam (~3°) with a small antenna they multiply this up to 35 GHz (Ka band) and scan forward. The antenna scans and is controlled to make the beam clear a safe height above the surface using the measured aircraft altitude and attitude. Using 30 mW the system detects small obstacles including wires out to about 3,100 ft. A design

using 250 mW is expected to operate to 10,000 ft range. The lower power unit was tested on a Bell Jet Ranger and a Cessna Skymaster. In these tests the standard 4.3 GHz altimeter measured height. The system worked well. However, it has not been used over water, and no systematic study of reflection from rough water at this frequency is available, at least not associated with this study by Honeywell. Millimeter waves reflect specularly off smooth water; hence some work on the radar cross section of small scale roughness is required.

For wingships it may be possible to use 35 GHz for both the forward scanner and the downward looking radar altimeter to provide a narrow beam that will follow wave surfaces. By suitable processing the mean height and variance are measured. Antennas at each wingtip, nose and tail sense attitude from differential height. The forward scanning radar at 35 GHz would detect obstacles with a 250 mW transmitter.

Salt Detector

A capacitive microbalance can detect very small amounts of deposited material. Quartz crystal microbalances detect microns of deposited material in space; this is greater sensitivity than needed for wingship engines. It should be possible to design such a detector to mount at critical points in an engine. Measurements in the hot section will, however, pose special problems.

Alternatively, salt might be inferred by monitoring engine performance. As a practical matter degraded performance (thrust, fuel consumption and etc. would indicate that washing is needed. During development internal monitors could check the correlation of salt and performance.

3.2.1.4 Development Required

Flight Control

Most sensors performing critical and unique wingship functions can be drawn from existing aircraft instrumentation. Present RLG inertial sensors, especially when matched with GPS, are adequate for navigation and to control the craft. The inertial systems must be aligned before flight, as usual. Because of the critical proximity of the water, continual radar altimetry is needed, and we believe that continual updating/realignment of the attitude system should be provided by means of multiple radar altimeters. A decision is need as to the use of conventional ~4 GHz altimeters, or to go to the narrow beam ~35 GHz. While differential GPS offers a possible alternate reference to align the attitude control system, in our view direct reference to the water is safest and exploits the necessary height measurement.

The principal development therefore consists of control system specification and creation of suitable control algorithms. The system links attitude and height sensors with the autopilot and suitable cockpit displays. It also affords navigation information, but this is not unique to wingships. In concert with definition/simulation of wingship flight dynamics development must take account of the nature of the sea surface. Steps include selection of sensors, selection of data bus and a flexible computer, and then the creation of software to be modified as calculation and simulation proceed. This would continue in concert with flight simulation.

Obstacle Avoidance

In this case an adequate sensor is not evident. While some form of radar is undoubtedly needed, development is needed to assure detection of small objects and especially high waves in the presence of sea clutter. Probably little hardware needs development, although experiments with prototype and new systems,

e.g., millimeter radar, is needed. The choice of cruising height and maximum operating seastate affects the level of concern about high and rogue waves.

In our view the necessary development steps are: analysis of the vast literature on sea clutter and target detection including any results with millimeter waves; measurements over rough water with the millimeter wave radar such as built by Honeywell (Both reflected sea clutter and effective range versus power would be investigated. Flight test may not be necessary.); choice of a system and tests from a fixed site or research vessel looking at the actual sea; integration into the flight control system and tests with the rest of that system.

Salt Detector

Salt detection must be coordinated with the engine manufacturers. Experiments with LUN or its equivalent using existing engines are possible without this sensor, if necessary. Review available microbalances, especially those capable of high temperature operation, then adapt one or more models to install in a test engine.

Seastate Forecasts

No development needed.

3.2.1.5 Cost and Schedule

Flight Controls

First year: One flight control engineer working half time over a calendar year to select optimum sensors and systems. The other half of his/her time the first year is devoted to defining algorithms to work with the rest of the aircraft.

Cost: $180 K

Second year: Full time engineer working with flight simulation.

Cost: $180 K

No hardware costs are included in this estimate.

Obstacle Detection

First year: Radar signature analyst works half time to look at current state of information on sea clutter.

Cost: $100 K

In parallel, test millimeter radar over rough water. This could be done from a platform.

Cost: $400 K

Second year: Select/build a prototype system and make measurements over actual sea from a platform or vessel.

Cost: $500 K

Third year: Integrate with flight control system and test with flight simulation.

Cost: $100 K

Salt Detector

First year: Review available microbalances or other possible instrumentation. Examine possibility of high temperature operation. One-quarter man-year.

Cost: $40 K

Second year: Build/purchase a prototype sensor and test.

Cost: $100 K

3.2.2 Actuators

This roadmap for actuators includes technologies required for wing flaps on wingships using a power augmented ram (PAR) system. The examined wingship sizes range from 150 tons to 5,000 tons in a series of size categories. Specific actuator requirements are provided for wingships of 400 tons, 1,000 tons, 2,300 tons, and 5,000 tons. (Note: tons are short tons). This roadmap's empirical basis is limited, because the largest wingship built to date is the Caspian Sea Monster with a full load weight of only 540 tons. The ORLAN and LUN wingships were about 150 tons and 400 tons respectively. U.S. designs range from 681 tons to 5,000 tons. These consisted of the Lockheed 1,362,000-lb Spanloader and a Douglas Aircraft 2,000,000-lb WIG-S - both designed under Advanced Naval Vehicle Concepts Evaluation (ANVCE) program, a recent Northrop M1.6 wingship (1,600,000 lb), and the AEROCON 10,000,000 lb wingship.

Although this roadmap is principally concerned with actuators, it is clear from topic research that the entire control/power system should be considered for actuation of flaps, ailerons, elevators, rudder and nozzles. It is evident that the "aircraft world" is leaning and heading toward "Fly-by-Light/Power-by-Wire" (FBL/PBW) systems in 21st Century aircraft. Reference is made to the USAF/Navy/NASA "More Electric Aircraft" program.

3.2.2.1 Requirements

Large wingships require actuators in locations such as ailerons, elevators, rudder and nozzles. Actuators may become an integral part of "intelligent structures" to modify structural elements and thereby minimize effects of high load conditions. However, horsepower requirements will be dominated by wing flap requirements. Therefore, information in Table I is restricted to this application. Flap actuator requirements are based on PAR takeoff assistance. PAR has considerable impact on loads imposed on wingship flaps during takeoff, depending on wingship speed and flap defection angle schedule.

Table 3-10 - Flap Actuator Requirements

Size Category: 400 Tons (based on LUN)	
Max. output force (lbs)	46,000
Max. output link speed (in/sec)	1.5
Horsepower	11
Link stroke (in)	4.5
Size Category: 1,000 tons	
Max. output force (lbs)	77,000
Max. output link speed (in/sec)	2.5
Horsepower	26
Link stroke (in)	8
Size Category: 2,300 tons	
Max. output force (lbs)	95,000
Max. output link speed (in/sec)	3
Horsepower	50
Link stroke (in)	9
Size Category: 5,000 tons	

Max. output force (lbs)	171,000
Max. output link speed (in/sec)	3.5
Horsepower	86
Link stroke (in)	10.5

3.2.2.2 State Of The Art

Actuator problems on existing large wingships and projected designs summaries follow:

General Background Information - This information covers Soviet wingship control systems, as described in Reference 1, provides a background for actuator discussions and discusses Russian design philosophy.

The wingship control surfaces -- elevator, flap, rudder, and aileron -- are designed for trim and control in the longitudinal (elevator, flap) and lateral (rudder, ailerons) axes. The elevator, designed for trim and pitch angle control, is usually sectionalized. A large elevator area is required for wingship trim in the takeoff mode. The angular deflection of the elevator ranges from -30° to +30° for first generation Soviet wingships.

The flap system, designed for trim and speed, and altitude control, occupies area (up to 15 to 20% of main wing area). A high degree of compensation is built into the design to reduce hinge moments. For service reliability it is usually sectionalized. The angular flap deflection ranges from -10° to +45°. Ailerons were combined with the flaps (aileron-flap) in the first generation Soviet wingships. The angle deflections are +/-(10° to 15°).

Rudders are designed for lateral plane control. They consist of two or three sections and a lower section designed for control in the hullborne (floating) condition. Angular deflection varies in the range from -30° to +30°.

Movable orifices and nozzles, as well as deflectors that rotate the propulsion jets, and vary lift and pitch moments (and lateral moments for non-symmetrical blowing) are included in the control devices group. The deflection angle of nozzles and orifices range from 0° to 25°.

Reference 1 points out that with high wingship speeds and relatively large control surface areas, loads on actuator drives and hinge moments are significant, resulting in the need for "powerful" drives. The first generation Soviet wingships control systems are based on non-reversible booster control as illustrated in Figure 3-21. According to Reference 1, "this device possesses high power and meets the service reliability requirements that are so important for high-speed wingships." Two-chamber hydraulic actuators are used as control surface drives, and they have mechanical and electrical control signal inputs. Since as a rule wingship control installations require considerable length, intermediate hydraulic actuators are built-in.

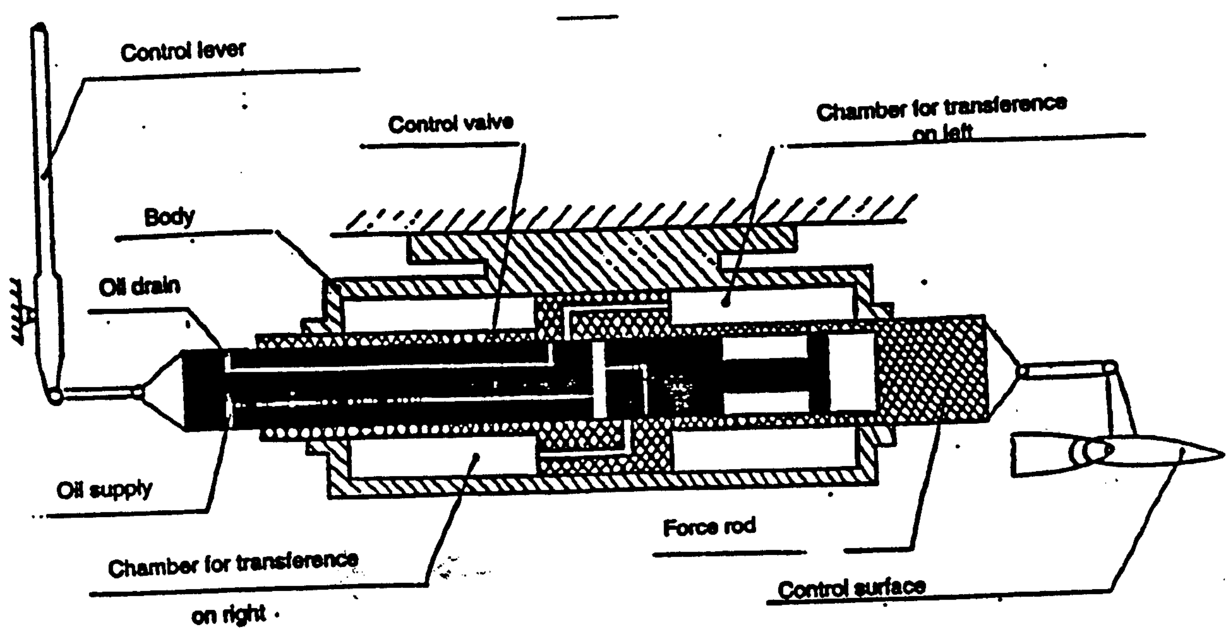


Figure 3-21 - Diagram of Non-reversible Booster Configuration

A flap control system "peculiarity" is a shock- absorber that is built into the drives. They are designed to protect the flap against shock loading from waves.

Takeoff and landing devices are designed to improve takeoff and landing aerodynamics. For first generation wingships, "blowing" PAR systems and hydroskis are part of these devices. The PAR system is designed to reduce takeoff speed. It consists of deflection devices for gas/air engine jets. The moveable orifices, nozzles, and deflectors are used for the control system. The engines generating PAR are mounted on pylons or inside the fuselage.

<u>Orlyonok Wingship</u>

The ORLYONOK (known in the U.S. by its designator ORLAN and is also called the A.90.150 EKRANOPLAN) has the following principal characteristics, according to References 2 and 3:

Overall length	190.3 ft; 58.0 m
Wingspan	103.4 ft; 31.5 m
Height	52.5 ft; 16.0 m
Fuselage length	151 ft.; 46.0 m
Wing area	3218 ft^2; 299 m^2
Wing chord	31.2 ft; 9.5 m
Aspect Ratio	3.3
Horizontal tail span	85.3 ft; 26 m
Horizontal tail area	1300 ft^2; 120.7 m^2
Weight, normal takeoff	110 tons
Weight, overload takeoff	125 tons

According to Reference 1: "Soviet working wingship prototypes of cargo versions have been built enabling the economics of future passenger carrying versions to be predicted." The fuselage is a relatively simple girder and stringer design, and like the wings it is divided into watertight compartments.

The NK-12 turboprop installation is mounted high at the fin and tailplane intersection to keep the intake far away from sea spray as feasible. The nose-mounted jet engines have pivoted exhaust nozzles. During takeoff the jet exhaust streams are directed beneath the wing to boost the ram-air pressure beneath the wing. On changing to cruising flight the nozzles are redirected to provide horizontal thrust accelerating the craft until cruising speed is reached. The takeoff jet units are then shut down. The jet units are located on the fuselage nose allowing the intakes to be in the nose contours in such a way to minimize aerodynamic resistance.

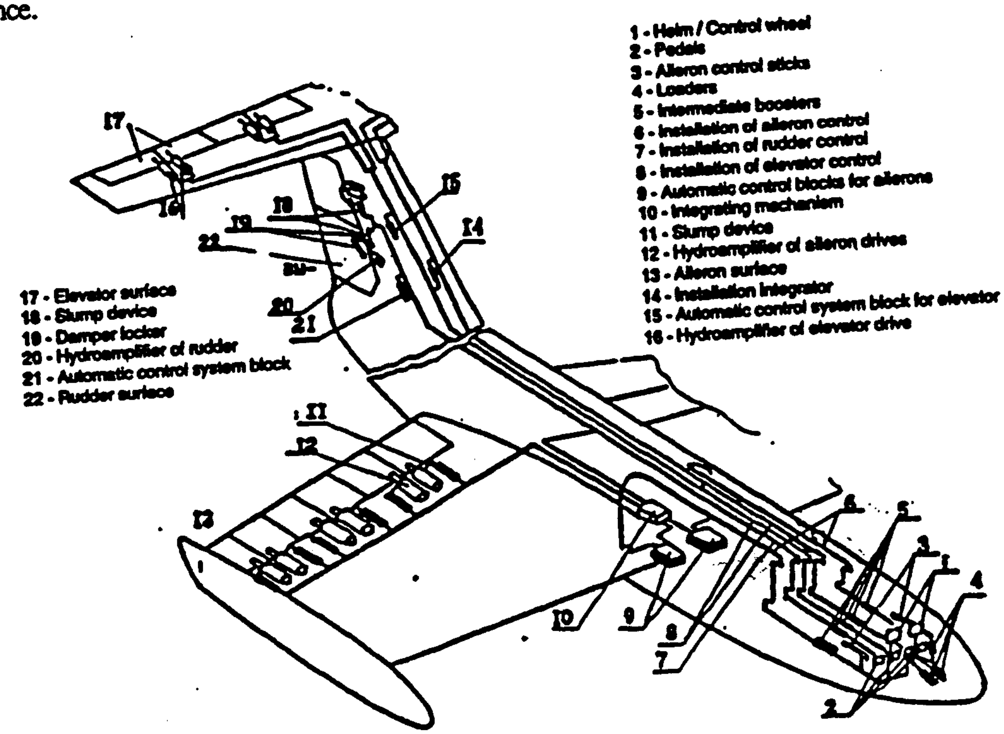


Figure 3-22 - Overview of ORLAN Control System

An overview of the 150-ton ORLAN control system is illustrated in Figure 3-22. This is taken from Reference 1, a translation of a Russian document. Item 13 is called an "aileron surface," but most likely it is really part of the "flap system," and the actuators described in Reference 1 are used in conjunction with this system.

Another diagram showing the flap system in isolation is in Figure 3-23. This refers to the actuators as being "pneumatic" (this may be an error in translation). The flap control system description covers both flaps and ailerons. It consists of the components shown in Figure 3-23. They are dual manual controls (control in aileron mode), dual control flap levers (control in flap mode), "loader," flight control devices, locking device for flap levers, "slump" devices, six combined KAU-120 sets, pneumatic dampers, flaps and ailerons control links, balances and sealing blocks. *[Meaning of "loader" and "slump" devices is not clear, and may be a poor translation.]*

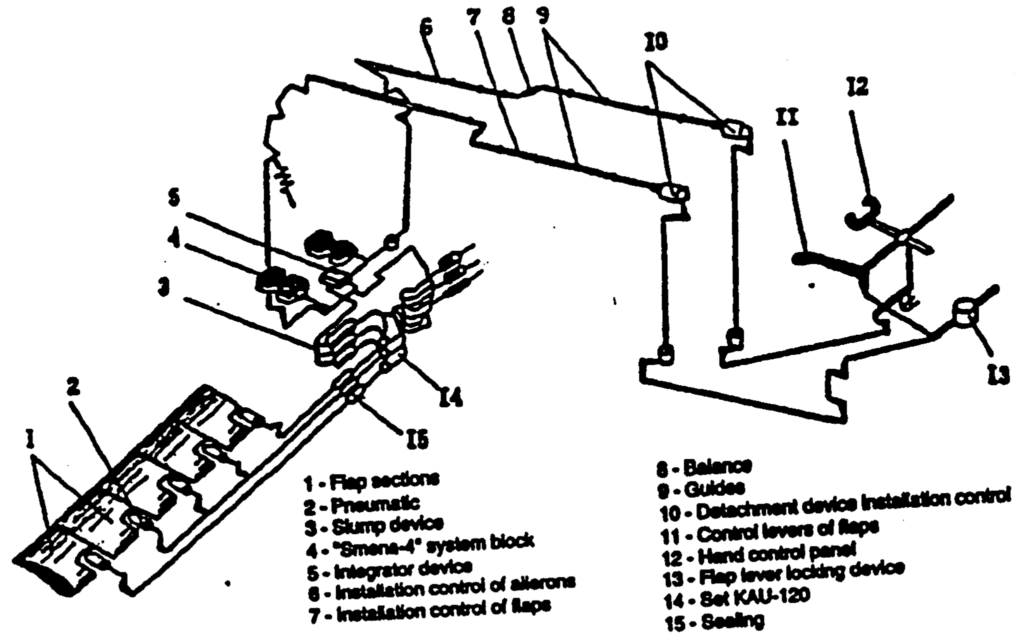


Figure 3-23 - ORLAN Flap Control System

LUN WINGSHIP

The LUN wingship was the first of this size built by the Russians. A second vehicle of generally the same design called SPASATEL was intended for rescue work. Latest report is that this wingship was never completed. Physical and performance characteristics, available outside Russia, are not as complete as those for ORLAN.

Principal Characteristics of LUN are as follows:

Total full load weight	400 ton s
Length, overall	242 ft; 73.8 m
Beam/Wingspan	144 ft; 44 m
Wing chord	43.6 ft; 13.3 m (est. based on Aspect Ratio of 3.3)

The flap control system description, in Reference 1, for LUN also covers both flaps and ailerons. The system shown in Figure 3-24 in part consists a control wheel for aileron mode, a control lever for flap mode, RP55-2A intermediate hydraulic actuators, loader, a trimming device, flight control instruments, an Automatic Control System (ACS), "slump" devices and "two-mode" hydraulic actuators.

The two-mode hydraulic actuator driving the flap has the following characteristics:

Maximum output force for flap extension	190 KN (42,716 lb)
Maximum output link speed	160 mm/s (6.3 in/sec)
Input link stroke	160 mm (6.3 in)
Output link stroke	400 mm (15.7 in)

Working pressure	210 kg/cm^2 (3,000 psi)

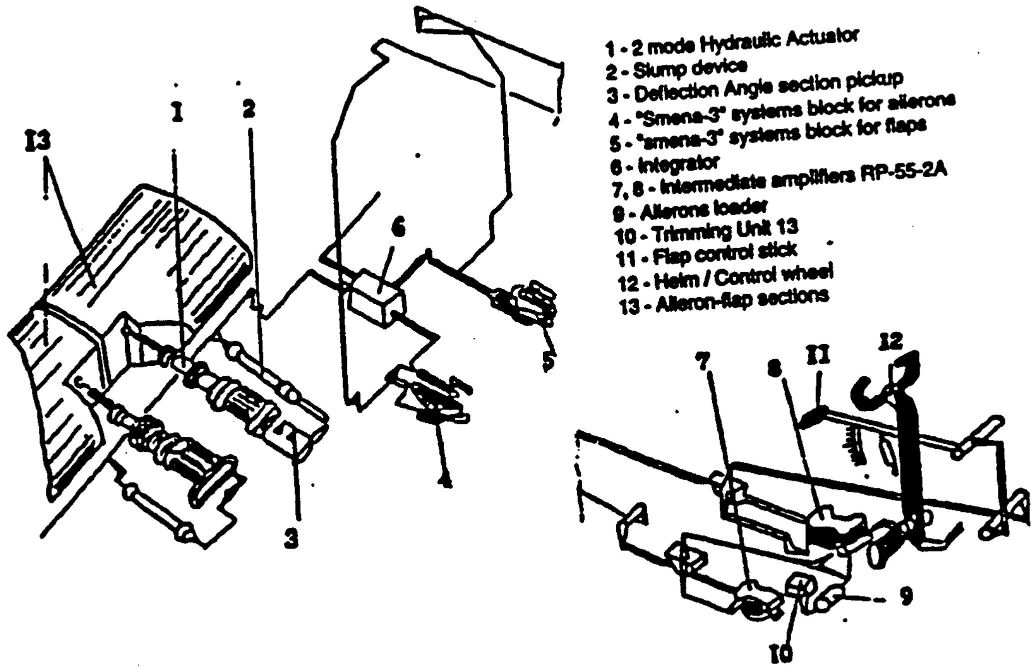


Figure 3-24 - LUN Flap-Aileron Control System

Two-mode pneuma-hydraulic dampers are built-in to the drives for safety of flaps, drives and structures while impacting the rough sea surface.

A typical LUN takeoff flight sequence as described by the Russians during the WTET meeting with CHDB in Nizhny Novgorod, per Reference 4, is:

Speed % takeoff	Wing Flap Deflection	PAR Nozzle Deflection	Thrust
0-10	0°	0°	20% max
10-30	0°	20°	max
30-45	10°	20°	max
45-60	15°	20°	max
60-100	20°	20°	max

Note: Cruise speed = 1.5 Takeoff speed

Flap deflection is programmed to increase as speed is increased. The hull is gradually lifted by aerodynamic forces to reduce the draft of the hull. This is to avoid large hydrodynamic loads on the flap when the draft of the hull is still large. Since the takeoff speed of 340 km/hr (184 knots) is approximately 65% of the cruise speed of 500 km/hr (270 knots) (at least for the LUN), the hull remains in contact with the water surface for a wide speed range despite PAR system activation.

The hydraulic actuator on LUN outputs about 40 hp, which is relatively large compared to hydraulic actuators used on even large aircraft today. However, there are comparable or larger actuators in terms of horsepower developed for the Space Shuttle Launch Vehicle, and development continues under the "More Electric" program for future use.

The literature on the Douglas Aircraft wingships (Wig-0 and Wig-S), Lockheed- Georgia wingship, Northrop, and AEROCON did not provide any actuator requirement information.

Recent Developments

"More Electric" Program

As mentioned in the actuator introduction, it is clear from researching the topic of actuators, that this wingship technology roadmap should consider the entire control/power system for actuation of flaps, ailerons, elevators, rudder and nozzles in a total systems context. It is evident that the "aircraft world" is leaning and heading toward "Fly-by-Light/Power-by-Wire" (FBL/PBW) systems on 21st Century aircraft. Therefore, a brief description of the USAF/Navy/NASA "More Electric Aircraft" program follows.

The More Electric Aircraft (MEA) and more recently the More Electric Initiative (MEI) concepts are based on utilizing electric power to drive aircraft subsystems which historically are driven by a combination of hydraulic, electric, pneumatic and mechanical power transfer systems. Increasing electric power use (More Electric) is the technological opportunity direction for aircraft power systems based on rapidly evolving advancements in power electronics, fault tolerant electrical power distribution systems and electric-driven primary flight control actuator systems. With this advancing technology, it will be feasible to use high power density electrical power components to drive the majority of aircraft subsystems. Each power transfer discipline on an aircraft requires specialized Aerospace Ground Equipment/Ground Support Equipment (AGE/GSE), personnel and deployment of these systems and support personnel to the theater of operations. Reducing the number of power transfer functions in turn has a major impact on the types and quantity of GSE required. Recent studies indicate this approach offers substantial payoffs in reliability, maintainability, survivability, reduced GSE, much-lower operations and support (O&S) costs, less impact on the environment (elimination of hydraulic fluid, associated solvents and monopropellant hydrazine) and improved performance. Recent technology advancements make this approach more viable. Government/industry planning to further develop and transition this technology is underway.

Power-By-Wire

Interest in Power-By-Wire (PBW) actuation systems described in Reference 5 is fueled by the many advantages offered by distributed power versus traditional aircraft centralized hydraulic systems. These advantages include:

- Increased survivability
- Improved aircraft maintainability
- Reduced ground service equipment requirements
- Reduced susceptibility to hydraulic fluid fires.

In addition, as PBW system designs improve in size and efficiency and future aircraft are constructed around such technology, advantages in system reliability and aircraft efficiency will increase.

When discussing PBW systems, three basic architectures have been the areas of main emphasis. These are defined as:

1. The Integrated Actuation Package (IAPTM) is an electrically powered actuator incorporating a constant speed electric motor, a servo-controlled hydraulic piston pump (servopump), a hydraulic actuator and a servopump controller. The integrated packaging and high power density of IAPs that make them applicable to aircraft are new.

2. The Electrical Back-up Hydrostatic Actuator (EBHA) is a dual channel system containing one conventional servoactuator channel and a second backup channel comprised of an Electro Hydrostatic Actuator (EHA) (also referred to as electrohydraulic) which is an electrically powered actuator incorporating a servo controlled, variable speed, variable direction electric motor and a fixed displacement piston pump. Both channels supply the same single actuator.

3. The Electromechanical Actuator (EMA) is an electrically powered actuator incorporating a servo controlled, variable speed, variable direction electric motor, a high speed gearbox with gear reduction and a linear ballscrew or geared rotary actuator.

Three types are shown in Figure 3-25. Lucas Aerospace and others in support of several aircraft and missile programs has been evaluated, developed, fabricated and tested each system.

To help speed transition of new aerospace initiatives to competitive U.S. technologies, the National Aeronautics and Space Administration's Dryden Flight Research Center developed a Systems Research Aircraft (SRA) Facility. Its primary goal is to accelerate transition of new aerospace technologies to commercial, military and space applications. The intent of flight testing new technologies is to eliminate perceived and real technical barriers. Both flight critical and non-flight critical experiments can be targeted for the SRA Facility. Flight critical experiments include systems such as electric actuation for critical surfaces and closed-loop, fly-by-light options.

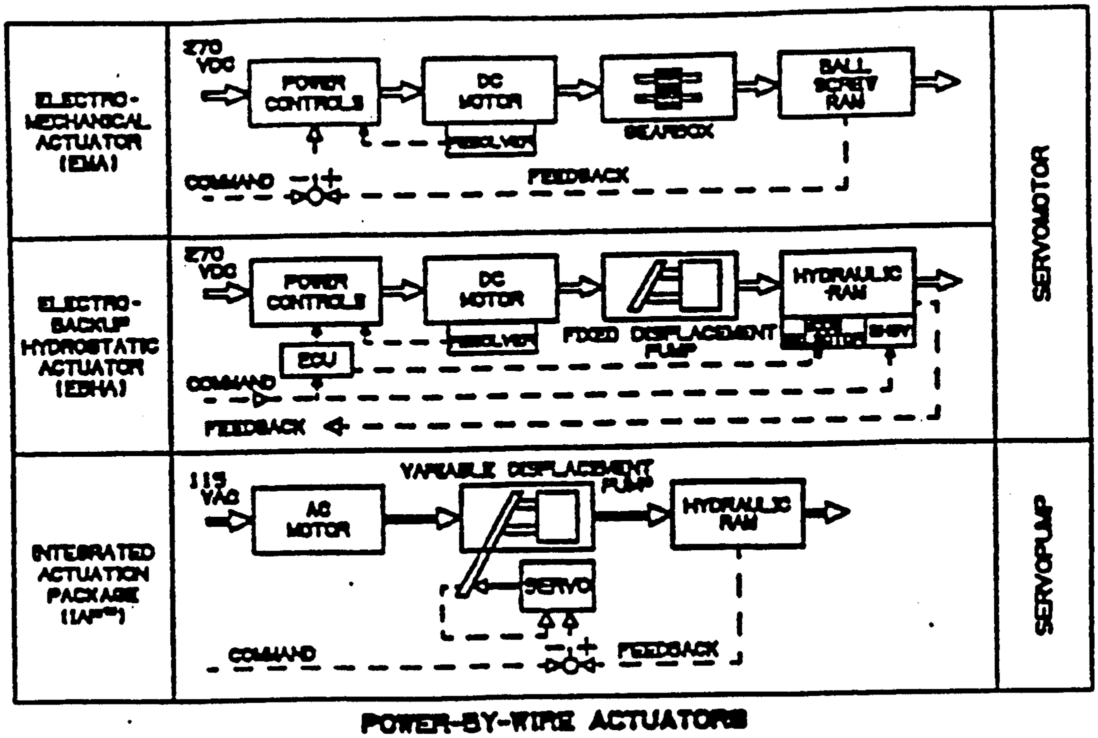


Figure 3-25 - Block Diagram of Power-By-Wire Systems

One major program using SAR is the Electrically Powered Actuation Design (EPAD) program. EPAD's purpose is to examine reliability and performance of advanced actuators. The EPAD program is a joint U.S. Air Force, U.S. Navy and NASA program. EPAD is flight-testing a Smart Actuator, Electrohydrostatic Actuator and Electromechanical Actuator. The tests will validate reliability issues of actuator-mounted electronics, power-by-wire with confined hydraulics and power-by-wire with no hydraulics.

Allied Signal built actuator bodies with composite materials, and the results are promising. This results in actuator unit weight savings.

NASA 757 FBL/PBW Demonstration Program

Costs drive the Fly-By-Light/Power-By-Wire technology to improve the U.S. competitive position, lower airline capital investment, reduce direct operating costs, reduce weight/fuel consumption and increase reliability (improve schedule performance). The program aims to provide lightweight, highly reliable, electromagnetically immune control and power management systems for advanced subsonic civil transport aircraft. The immediate objectives are to develop technology for confident application and certification of integrated FBL/PBW by cooperating with industry to provide risk reduction for costs, safety and certification, proof of technology maturity, maintainability and reduced or simplified manufacturing, performance improvements and added value to the airlines, lower cost and less time consuming methods of accomplishing certification.

Studies show that ultra-reliable power-by-wire approach offers major system level payoffs for commercial aircraft by reducing airline up-front costs by 3.2%, reducing direct operating costs by 1.5% and increasing system reliability by 16%.

The program is fully funded and stretches through FY 99. The PBW work is contracted with a Douglas team. The FBL work is under Boeing contract. NASA has purchased a 757 test bed. Ground tests are schedules through FY 97; civil flight tests in FY 98 leading to integration and evaluation by FY 99. The power level of the largest actuator in this program is about 25 hp.

NASA Advanced Launch System Actuator Development

The Power Technology Division of the NASA Lewis Research Center, in conjunction with several contractors, is developing electromechanical actuators (EMA) in support of the Advanced Launch System. These are the largest such actuators available or in development that may be applicable to large wingships. Table II, provided by NASA, summarizes actuator characteristics. Those listed on the right side of the table are of particular interest. These range up to 68 hp.

TABLE 3-11

ELECTROMECHANICAL ACTUATORS APPLICABLE TO NATIONAL SET OF LAUNCH VEHICLES

REQUIREMENTS	20 Hp EMA FOR COMMERCIAL ELV				40 Hp EMA		[illegible]		
	CENTAUR	ENGINE PRE-VALVE	TITAN III STAGE 1*	ATLAS BOOSTER	STS FLT CONT. OUT ELE	STS FLT CONT. IN ELE	ALS PREL	STS TVC	[illegible]
STALL LOAD (LBS)	1610	X	29,790	10,750	54 K	65 K	48,000	74,400	96,840
DYNAMIC LOAD (at actuation rate) (LBS)	1191	X	11,330	7,510	39 K	48 K	32,000	48,000	
ACTUATION RATE (DEG/SEC)	6	X	10	9	30	30	15	10	10
ACTUATION POWER (HP)	0.5	2.1	4.3	6	13.7	28.5	32.8	41.6	68

* ("Applicable TVC for ALS and MOOG Position Statement", MOOG, INC., Missile System Div., East Aurora, NY 14052)

X - PARAMETER NOT APPLICABLE/AVAILABLE

The Appendix contains specific information from actuator manufacturers elaborating on these characteristics for the larger sizes.

3.2.2.3 Preferred Technologies

In view of the emphasis and progress being made in the area of electric actuation as described above, the preferred technology for actuation of various devices, particularly wing flaps, may be electric. However,

much is known about hydraulic systems, whereas, there is much to be learned about large electric actuator systems. Unknowns may appear during large electric actuator development, which may negate some of their advantages. A high level of redundancy or fault tolerance is necessary in large, costly wingships.

However, to place these issues in perspective, the advantages and disadvantages of hydraulic and electric systems are outlined below.

ADVANTAGES

Electrohydraulic Actuation

- Lightest, most compact actuator (overall secondary power system may be heavier)
- Thermal management is straight forward
- Broader industrial base; more field

Electric Actuation

- Overall secondary power system may be lighter
- Simplified maintenance
- Greatly improved power experience efficiency

DISADVANTAGES

Electrohydraulic Actuation

- Complex centralized hydraulic supply and distribution system
- High maintenance, requiring specialized personnel and equipment
- Higher wasted power

Electric Actuation

- Actuator itself is larger and heavier
- Thermal management is very difficult
- Requires development funding

ADVANTAGES

EMA

- Total elimination of high-pressure oil
- Good MTBF (Mean Time Between Failures)
- Lowest heat generation

EHA

- Minimal common-mode failures
- Good PLOC (Probability of Loss of Control)
- Lowest weight
- Best power efficiency

IAP

- Minimal common-mode failures
- Good PLOC
- Moderate Weight
- Best accelerate capability
- Simple, low-cost controller

DISADVANTAGES

EMA

- Backlash unacceptable for flutter (>0.007 in)
- Heavy

EHA

- MTBF worse than FBW (Conventional, FBW) actuator
- Dynamic stiffness can be a problem

IAP

- MTBF worse than FBW actuator
- Dynamic stiffness can be a problem

- Difficult to package in tight envelope
- Impractical to make jam-proof
- Problems with threshold, resolution, and small-signal response
- Significant heat generated by charge pump and swashplate servo

The introduction of EMAs into aircraft primary flight controls was slowed by the inability to provide redundant actuators for control surfaces. If two EMAs operate in parallel, then jamming one locks the control surface in place. Some new "fail-operate" rotary EMA designs get around this problem. Whether linear EMAs do, this needs to be explored.

As indicated above, actuator technology remains a tradeoff. Hydraulic actuators, be they conventional, IAP or EHA, are more suited to high powers, frequent precise positioning, multiple channel systems. Electric actuators are more suited to more moderate power levels, infrequent "bang-bang" operations and single channel systems. Developments need to be monitored to determine their impact on these statements.

3.2.2.4 Deficiencies

In terms of wingship size categories, the deficiencies are as follows:

400 Tons - Actuators up to a load capacity of about 46,000 lb or about 10 to 12 hp depending on actuator link speed requirements.

No deficiencies envisioned. Either existing hydraulic actuators, or those electric types developed for various existing aircraft can be applied with minimum risk, particularly in the time frame the U.S. would construct this size wingship.

1,000 Tons - Actuators up to a load capacity of about 77,000 lb or about 25 to 30 hp depending on actuator link speed requirements. Each actuator package contains two actuators working in parallel and there are two packages driving each flap section and that flap section sizes are reasonable. These packages need to be synchronized so as to not to introduce a twist in the flap structure.

No deficiencies envisioned. Either existing hydraulic actuators, or those electric types developed for various existing aircraft can be applied with minimum risk.

2,300 Tons - Actuators up to a load capacity of about 95,000 to 100,000 lb or about 50 to 60 hp depending on actuator link speed requirements. Each actuator package contains two actuators working in parallel and there are two packages driving each flap section. These packages need to be synchronized so as to not to introduce a twist in the flap structure.

Some deficiencies envisioned. The technology of existing hydraulic actuators or those electric types developed for various existing large aircraft or spacecraft boosters (launch vehicles) needs exploration, trade offs examined and applied with moderate risk.

5,000 Tons - Actuators up to a load capacity of about 170,000 lb or about 86 to 100 hp depending on actuator link speed requirements. Each actuator package contains two actuators working in parallel and there

are two packages driving each flap section. These packages need to be synchronized so as to not to introduce a twist in the flap structure.

Although hydraulic actuators exist in this size category, some development may be required to achieve reductions in weight. The technology for either existing hydraulic actuators or those electric types developed for various existing large aircraft or spacecraft boosters (launch vehicles) can be applied with the necessary development. However, because the future of large booster development is unknown, a wingship program in the 5,000-ton category may not reap the benefits of such a development. Hence, cost and an associated moderate risk will be impacted.

3.2.2.5 Development Required

Allied Signal built actuator bodies with composite materials, and the results are promising. This results in actuator unit weight savings. The technique needs to be applied to larger actuators, weight reduction estimates made and demonstrated. This may require some development.

If electric actuators and the FBL/FBW philosophy is selected for the main path on the "actuator roadmap", it is clear that the More Electric program will provide appropriate stepping stones up to a point. The 5,000-ton wingship program involves stepping stones beyond those expected from the More Electric program.

3.2.2.6 Cost and Schedule

400-ton wingship actuators
2 years at $2 million/year
Total $4 million

1,000-ton wingship actuators
3 years at $2 million/year
Total $6 million

2,300-ton wingship actuators
4 years at $2 million/year
Total $8 million

5,000-ton wingship actuators
5 years at $3 million/year
Total $15 million

3.2.3 Simulation and Modeling

The use of simulators is becoming widespread not only in the aerospace field, but in other facets of technology - indeed of everyday life including entertainment. Simulators are indispensable for new vehicle development of whenever the control system needs to cover a large operating envelope or involves complex mechanical, hydraulic and electronic components. In digital control system development simulator use is almost axiomatic — the verification and validation of control law software is done on simulators. It's logical to use simulators in such a costly enterprise as the design, construction and testing of large wingships. This section's objectives are to summarize the requirements for high fidelity fight simulators for large wingships, to survey simulator state of the art appropriate for wingships, to examine any wingship modeling shortfalls, and make a first cut estimating the cost and schedule for large wingship simulators.

3.2.3.1 Simulator Requirements And Utilization

For effective utilization in engineering development, a simulator must meet several requirements. In contrast with procedures training simulators used by operational military squadrons and airline companies, engineering simulators don't have each cockpit indicator or switch in place, expensive motion platforms or sophisticated visual scene generators. Instead, they have a high degree of fidelity of the vehicle dynamics, including the feel of pilot control devices. Therefore, even an engineering simulator requires fairly elaborate cockpit development. In a wingship simulator the importance of the static balance involving the centers of gravity and buoyancy needs emphasis. Most of time the simulator must support control system development. Almost parallel with control system development is the investigation of the wingship handling qualities. With no wingship operational experience in this country, applying airplane handling qualities and criteria to wingships can not be taken for granted. The simulator needs to reproduce the effect of various flight control and propulsion systems failures so actual operation can be initiated with some measure of safety. To extract as much information as possible from initial wingship flights and testing, the simulator should be extensively utilized for flight test mission planning and ground and flight crew training.

3.2.3.2 State Of The Art

NASA's Dryden Flight Research Center actively uses simulators, both for engineering development and to support flight research. Specific aircraft simulations range from large four-engine subsonic transports to highly maneuverable fighters with digital fly-by-wire controls. A survey of these simulators indicates that in simulation technology is at the point where the computing hardware performance is of relatively minor importance. The complete mathematical model of large wingships, including equations of motion, control system dynamics, propulsion system and graphic display can be processed by computers readily available at modest cost (less than $250,000). Since wingship acceleration while airborne isn't large, fixed base simulations should meet the requirements. Experience with NASA' s simulators indicates the crew section requires the most development including a programmable force feel system, cockpit displays and a computer-generated visual scene. None of these are off-the-shelf items and must be designed and fabricated for each application.

Figure 3-26 shows a schematic of the X31 airplane simulator. This piloted, six degree-of-freedom simulator consists of elements representative of a vehicle with a fly-by-wire control system that includes thrust vectoring. The purpose of showing on this figure the full complexity of the X-31 simulator is not to describe the function of each module, but to illustrate the buildup of a fight simulator that is expected to meet the requirements described earlier. Actually, this simulation has the capability of an all-digital

simulation in which all mathematical models of vehicle subsystems, including the visual scene, are processed by the Silicon Graphics 460 computer shown in the upper right of the figure. Alternatively, the processing of the control laws, structural and anti-aliasing filters can be delegated to the actual flight control computers, designated as FCC #1, 2, 3, and 4 in the lower middle; thereby this simulator becomes a hardware in-the-loop variety. For software development the simulator incorporates a Silicon Graphics 440 computer and additional terminals. The components shown on the lower left are necessary only if the simulator needs to interface with the flight test vehicle instrumentation system during flight tests. The various simulator elements communicate through the Universal Memory Network shown in the middle. The pilot cockpit, including a programmable force-feel system, digital display indicators, all instruments and switches, is in the upper middle of the figure.

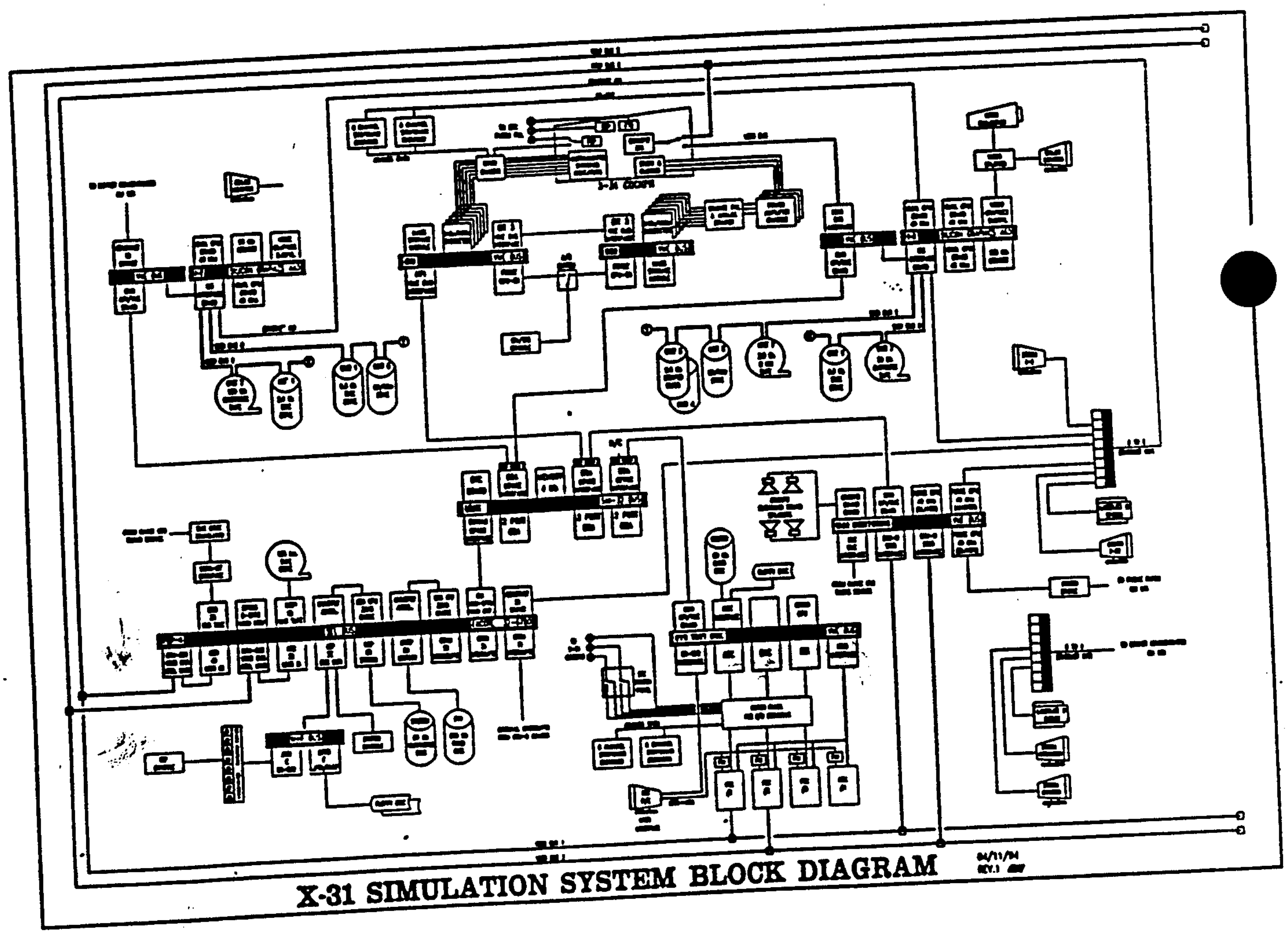


Figure 3-26 - X-31 Simulation System Block Diagram

The specification, design, subsystem integration, and validation of a simulator comparable to that of the X-31 airplane is a major task and should be initiated early in flight vehicle development.

3.2.3.3 Mathematical Models

Airframe. The wingship airframe modeling does not present technical difficulties over the modeling of conventional airplanes. Because of the short wingspan and relatively stiff structure, wingships can he modeled as a rigid body whose weight and moment of inertia characteristics are simple functions of fuel and payload. Since the wingship is regarded as a single rigid body, the classical Euler's equations of motion can be derived with respect to a set of axes fixed to the body's center of gravity. The orientation of the body-fixed axis system is a matter of choice - generally stability axes are preferred for longitudinal dynamics and a body-fixed system is used for the lateral-directional dynamics.

Hydrodynamic Modeling. Reference 1 states that "the takeoff and landing processes of a seaplane are most complex since they involve an interaction of the hydrodynamics of unusual geometric forms with the aerodynamics of the wing and tail surfaces." The use of the power augmented ram effect, or PAR, for wingship application complicates hydrodynamic modeling even further. Currently no validated analytical methods describe completely the hydrodynamics of wingships. Only empirical relationships are available from Reference 1 to describe quantitatively hydrostatic stability and such hydrodynamic phenomena as porpoising, drag and spray characteristics, and impact loads in rough water. While these empirical relationships are useful for initial simulator studies, for specific configurations the required hydrodynamic data should be collected from towing tank tests conducted in accordance with Froude scaling laws, such as those reported in Reference 2.

Aerodynamics. Although wingship aerodynamics is similar to that of conventional subsonic airplanes in free air, modeling of aerodynamic forces and moments in ground effect requires special care. Wingship aerodynamics is simpler due to the absence of compressibility and air density variations, but complete force and moment coefficient data should be obtained both in free air and in ground effect. Ground effect noticeably influences the flow around aircraft up to a height equal to the wing span with most of the beneficial effects of reduction of induced drag and increase of lift concentrated at heights less than 50% of the mean aerodynamic chord (MAC). Thus a wingship simulator should have complete aerodynamic force and moment data tabulated at height-to-MAC ratios of .1, .2, .4, .75 and in free air. These test heights will hopefully reproduce the dependence of the forces and moments on height with sufficient fidelity. In addition to the height dependence, the lateral directional forces and moments in ground effect also depend on the roll attitude. This dependence arises from the fact that in a banked attitude the ground proximity affects the left and right wing differently. The obvious testing difficulty requires the numerical estimation of some unusual wingship aerodynamics. In Reference 3 wind tunnel data on various configurations are surveyed and the need for full scale flight test data is emphasized. While some static aerodynamic data on a realistic wingship configuration is reported in Reference 4, forced oscillation test data to obtain damping derivatives is unavailable in wingship aerodynamics literature.

Atmospheric turbulence and seastate effects. When white noise passes through a first order filter, one with the transfer function of $1/(\tau s+1)$, the result is a stochastic process typical of many physical phenomena. With a suitable choice of τ, the result may be used as an atmospheric turbulence model or the model of the terrain seen from an airplane in straight and level fight. Most simulators model atmospheric turbulence by computing linear and angular gust velocities from white noise passed through "gust filters."

These filters are defined by the requirement that their output produce specific turbulence spectra. This procedure's applicability rests on the assumption that atmospheric turbulence is both isotropic and stationary. Airplane operation experience indicates that near the ground this assumption is not exactly valid, and discrete gusts and wind shear must be considered. High fidelity wingship flight simulations should include the above water height variation due to waves and swells. This height variation can be represented as a stochastic process similar to modeling atmospheric turbulence. The spectral characterization of waves is different from atmospheric turbulence in intensity and wavelength. Nevertheless, height variation can be simulated as filtered white noise with appropriate selection of filter characteristics.

Initial simulation of the mean height under the wingship in the presence of sea waves and swell waves is under way at NASA Dryden and summarized in Reference 5. A simple computer program, using a random number generator, assigns the MAC mean height over sea waves and swell waves as a function of vehicle distance traveled. The program only needs input on seastate and swell condition.

Actuators and sensors. Mathematical modeling of wingship actuators is straightforward and closely follows large airplane procedures. Since wingships are not required to be highly maneuverable there is no requirement for fast control surface actuation system. For initial simulation studies an actuator model of the transfer function form of $1/(\tau s+ 1)$ would probably be sufficient, with the values of τ ranging between .1 and .2. As test data becomes available the model can be refined to include the dynamics of the servovalve, and such nonlinearities as position and rate limits, and hysteresis. As a point of reference for large wingship actuation requirements, an experimental installation in a medium-size transport configured to conduct landing gear dynamics tests for NASA uses a hydraulic system with 3,000 psi working pressure and power ram capacity of 125,000 lbs. The system requires a hydraulic fluid flow rate of 100 gallons per minute per cylinder, and is capable of a ram rate output of 10 to 15

inches per second, depending on the load. The physical characteristics of the actuation systems, whether hydraulic or electric, can be accurately modeled and requirements assessed before hardware is fabricated.

Wingship sensor simulations should include three-axis angular rate sensor, linear accelerometers, inertial navigation units, or alternatively, GPS receivers, and angle of attack and sideslip sensors. Airplane simulators routinely model the dynamics of these sensors, so that the mathematical model of most sensor types would be available for wingship simulators. The mathematical modeling of less conventional sensor subsystems, such as radar altimeters or electrostatic height sensors, needs additional development.

Control system dynamics. In order to meet previously mentioned requirements, the correct flight control system simulation is especially important. In addition to pilot controls and hydraulic actuation systems, the control system must include mathematical models of all mechanical and electronic elements. Large wingships will likely have fly-by-wire, which is completely electronic controls saving weight and facilitating implementation of various autopilot modes. While simulating fly-by-wire controls for new airplanes has been done, care must still be taken to include the actual sampling rates, word size, and computational delays in simulations.

Propulsion system and PAR. Wingship propulsion system simulation requirements can be met with a relatively simple mathematical model. Since internal engine parameters are normally complex, non real-time engine decks, the total fight simulator is only required to show the varying engine thrust effects, asymmetric thrust effects, and provisions for thrust vectoring to simulate PAR. Experience with other

simulators shows that simple tabular function of thrust with throttle position and airspeed for each engine is usually sufficient.

Linearization and analysis tools. Incorporating provisions to obtain linear mathematical models for the analysis of these models is not strictly a simulation task. It has been found, however, that by doing so ensures commonality between the linear and nonlinear mathematical models. The linearization is performed numerically, and is especially advantageous when the aerodynamic and propulsive forces are tabulated in coefficient, rather than derivative form. Linear systems analysis is greatly facilitated if the simulation is linked to one of the widely used matrix analysis and graphics tools.

3.2.3.4 Technology Uncertainties

Most of uncertainties in wingship flight simulator fidelity are those associated phases of its flight in which analysis or subscale testing is too difficult or nonexistent. These phases include conditions in which the vehicle is not in equilibrium, that is, it is either accelerating or transitioning between planing on the water surface and airborne flight. Although a thorough description of both theoretical and experimental results on PAR is given in Ref. 6, no simulation incorporating these results has been validated against full-scale test data. One possible data source comparing simulation and actual test data may be Russian design organizations that participated in large Soviet wingship development.

There is little or no published experimental data on the damping derivatives in ground effect. Initial simulation efforts may resort to the free-stream values of the damping derivatives obtained from forced oscillation wind tunnel data, or possibly from parameter estimation applied to flight data. Again, the source of suitable flight data obtained in-, and out-of-ground effect may be Russian design bureaus.

Ground effect on the aerodynamic derivatives is uncertain if the surface is not smooth, which would be the case in the presence of waves and swells. The simulation fidelity in predicting performance degradation or the deterioration of the riding qualities is not established.

3.2.3.1 Cost And Schedule

Wingship size does not significantly impact the flight simulator cost. A possible exception is a larger cockpit with dual pilot controls for very large wingships. Both hardware and software costs depend on simulation location. An existing simulation facility, where infrastructure consisting of suitable space, the electrical and signal distribution systems, computers, various peripherals is already available, would be the most logical choice. At such a facility the largest hardware tasks are the design and fabrication of the cockpit, and the integration of the various subsystems. With modest acquisition of new computing equipment, the simulation hardware cost in today's dollars is between $800,000 and $1,000,000. Simulation software is available from many sources, including government-owned laboratories, such as NASA Dryden. Most of the needed software for wingship simulation is public domain, but it requires modifications in aerodynamic and hydrodynamic data handling. The initial mathematical model development, software coding and hardware buildup requires approximately five engineers with experience in aero/hydrodynamics, stability and control, systems integration, computer system analysis and electronic design. After initial development simulator operation requires one software engineer, a hardware engineer and an electronic technician.

Wingship simulators are developed in several phases, the first is an all-digital, unpiloted simulation, processed by the computer in a batch mode. As software and hardware elements are available, they are

gradually integrated into the simulator. Based on piloted simulation development, the total development time for a usable fixed-base, nonlinear piloted simulator is estimated to be between nine months and a full year.

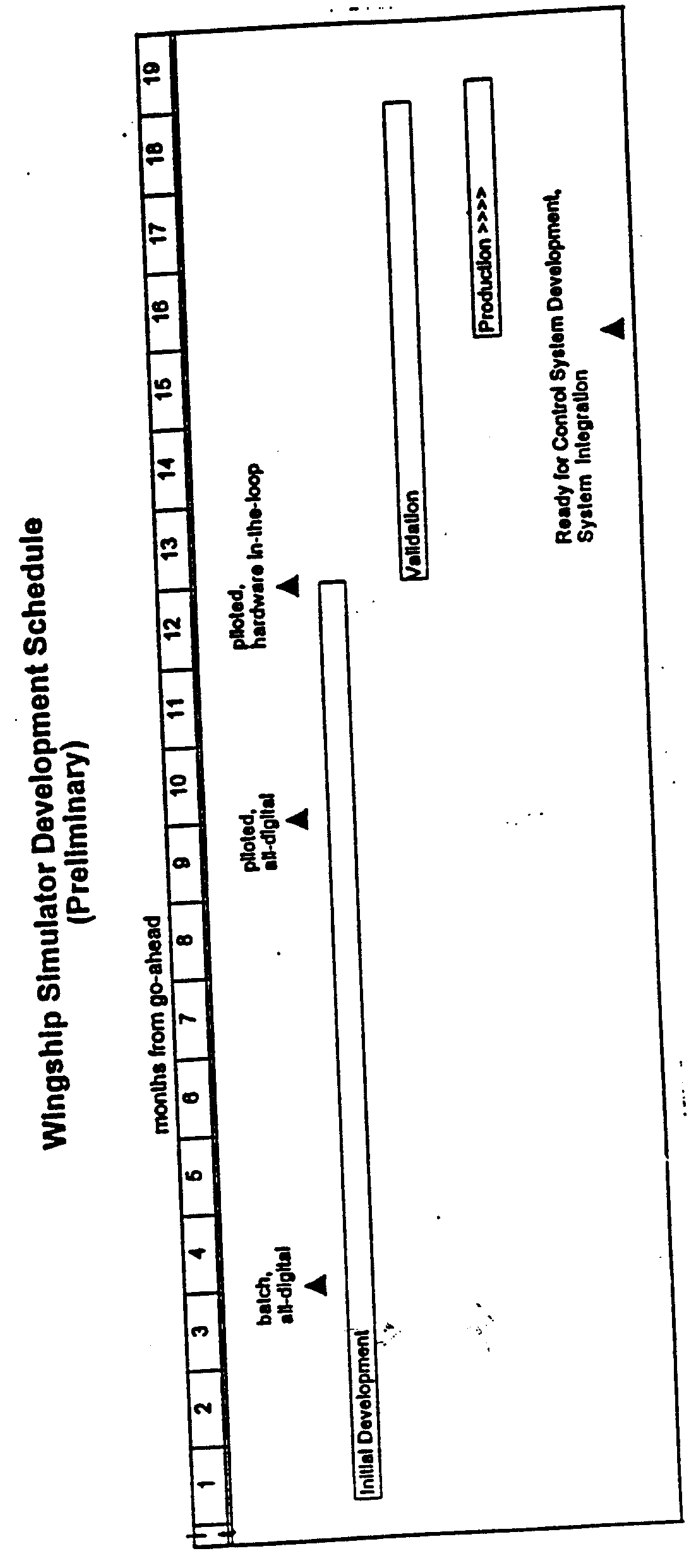


Figure 3-27 - Wingship Simulator Development Schedule

4. Related Areas

A wingship, being part ship and part aircraft, will require modification to design and testing procedures normally used for aircraft and ships. The high speeds and power involved suggest that of the two the normal aircraft procedures are the best points of departure.

Procedure modifications should include any additional features, sea-sitting habitability for example, that wingships require and take advantage of any simplifications (e.g. no pressurization) wingships permit.

The most impacted functional areas are design methodology and flight test.

4.1 Design Methodology

This section describes a wingship design approach. It borrows freely from modern general design methods (which, in principle apply to any engineered product), from proven approaches to subsonic transport design and from what we know about the Russian design methodology. The result is a tentative wingship-specific design method. The apparent deficiencies in this tentative method suggest promising method improvements which then become the subject of a program to develop these methodology improvements.

The tentative method also indicates genuine technical uncertainties. Resolving these uncertainties is part of the rationale for selecting the technology topics in earlier roadmap sections and for the fight test roadmap.

4.1.1 Wingship Design Requirements

Of all existing modern vehicle requirement sets, the subsonic transport airplane requirements are the closest to the wingship. And, the subsonic transport airplane is the point of departure for developing a representative list of wingship requirements. One could argue that seaplane or ship requirements might match fairly well. We rejected the seaplane requirements set as a departure point because no modern, complete and easily accessible seaplane requirement set examples are available. Further, seaplane design is not an active academic course in contemporary colleges and universities. The wingship shares some features with high powered planing boats. However, a major difference is that dynamic pressure of water supports the planing boat, whereas the dynamic pressure of the air supports the wingship. The difference in density (a factor of 800) results in irreconcilable differences in design requirements.

To develop a representative set of wingship design requirements, we modified the design requirements for a subsonic transport described in Table 4-1. A wingship doesn't need to meet some of these requirements (such as climb gradients and altitude capabilities) and will have much different numerical values in some requirements (such as takeoff distance). Also, the selected mission type will lead to additional requirements sets. For example, the missile magazine type of vehicle will have a sea-sitting requirement, and the hauler will have loading and unloading facilities requirements.

DESIGN REQUIREMENTS FOR A SUBSONIC TRANSPORT
Payload Description
Range and Reserves with Payload
Cruise Speed and Altitude Requirements
Takeoff and Landing Field Lengths with Temperature Altitudes and Runway Bearing Capacities
Applicable Airworthiness and Environmental Regulations

Table 4-1 - Design Requirements for a Subsonic Transport

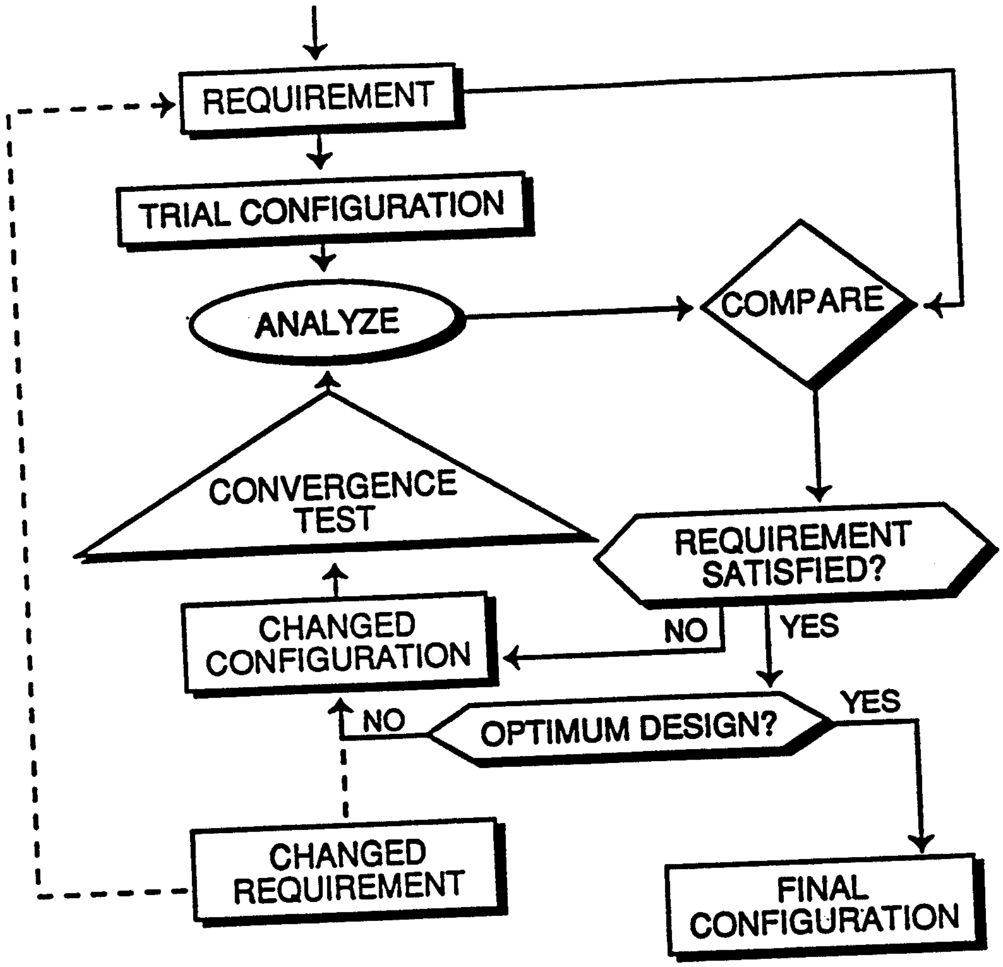
Table 4-2 is a set of requirements, constraints and objectives for a missile magazine wingship developed by modifying Table 4-1 for the differences between wingships and subsonic transport aircraft.

DESIGN REQUIREMENTS FOR A MISSILE MAGAZINE WINGSHIP
Payload Description. (vertical launch system?)
Range and Reserves with Payload. (2700nm, shoot, and return?)
Ferry Range (2700nm?)
Minimum Cruise Speeds or Maximum Block Times
Minimum Acceleration during Gross Weight Takeoff in Given Seastate
Seastate Requirement for Takeoff, Landing, and Sitting on Station Habitability
Applicable Airworthiness and Seaworthiness Regulations

Table 4-2- Design Requirements for a Missile Magazine Wingship

In addition to the requirements and constraints described above, the design team needs a goal. For transport aircraft, this goal is frequently to minimize direct operating costs. For military systems the goal is frequently to minimize life cycle costs. More recently, because of severely constrained budgets, there is a tendency to emphasize acquisition cost of the first few units. In any event, such a measure is required. For the missile magazine wingship, an appropriate optimization goal may be acquisition cost of a fleet sized to provide persistence and firing rate within the action radius. An approach being used on one current cost constrained program is to maximize a set of technical and mission performance measures subject to the constraint of unit fly away cost for a specific number of units.

There is always the possibility that the set of requirements and constraints is internally contradictory and cannot be met within the current technology. For this reason, the early part of any design process requires some iteration on requirements. Figure 4-1 from (Reference 1, page 16) indicates the iterative nature of this process. Once this top-level iteration has proceeded to the point that it is clear that requirements and constraints can be met within the existing technology, then the design problem is well posed.



GENERAL DESIGN PROCEDURE

Figure 4-1 - General Design Procedure

Then, the general design process is to search for the solution that maximizes, or minimizes, the objective function while meeting all requirements and constraints. Figure 4-2 illustrates this process. Reality is often more complex than Figure 4-2 indicates. The number of constraints may be too many to show on a two-dimensional chart. More than one objective function is being used. The various continuous curves and surfaces, shown if Figure 4-2, may actually be discontinuous with awkward jumps and multiple values. These discontinuities and multiple values typically occur when multiple design approaches and configurations approaches have different advantages in different areas of the parameter space. A systematic approach to any design problem must accommodate all these features.

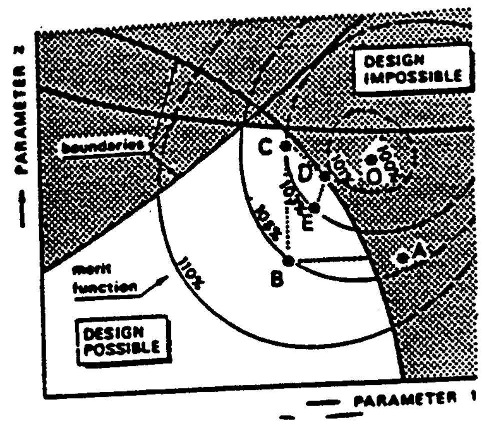


Figure 4-2 - Graphic representation of design optimization

4.1.2 Candidate Design Methods

Figures 4-3 and 027 are candidate design loops for subsonic transport aircraft design. The Figure 4-2 is more generic and qualitative. The second chart is the more definite top level logic that could be, and in many cases is, convert into a single aircraft design computer program. The flow in Figure 4-4 can be a part of that in Figure 4-3. Specifically, the loop in Figure 4-4 replaces steps five through eleven in Figure 4-3.

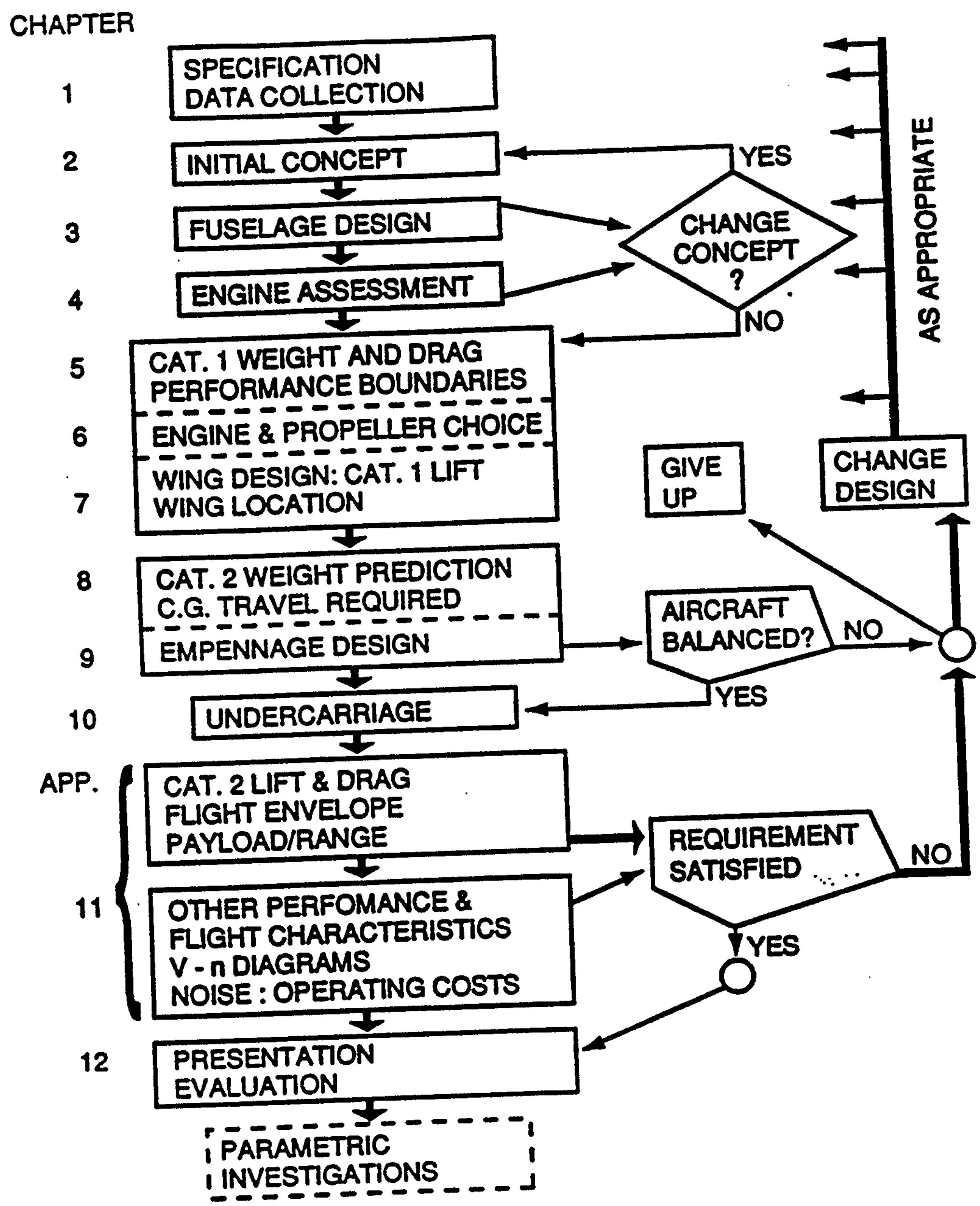


Figure 4-3 — Survey of the initial baseline configuration design

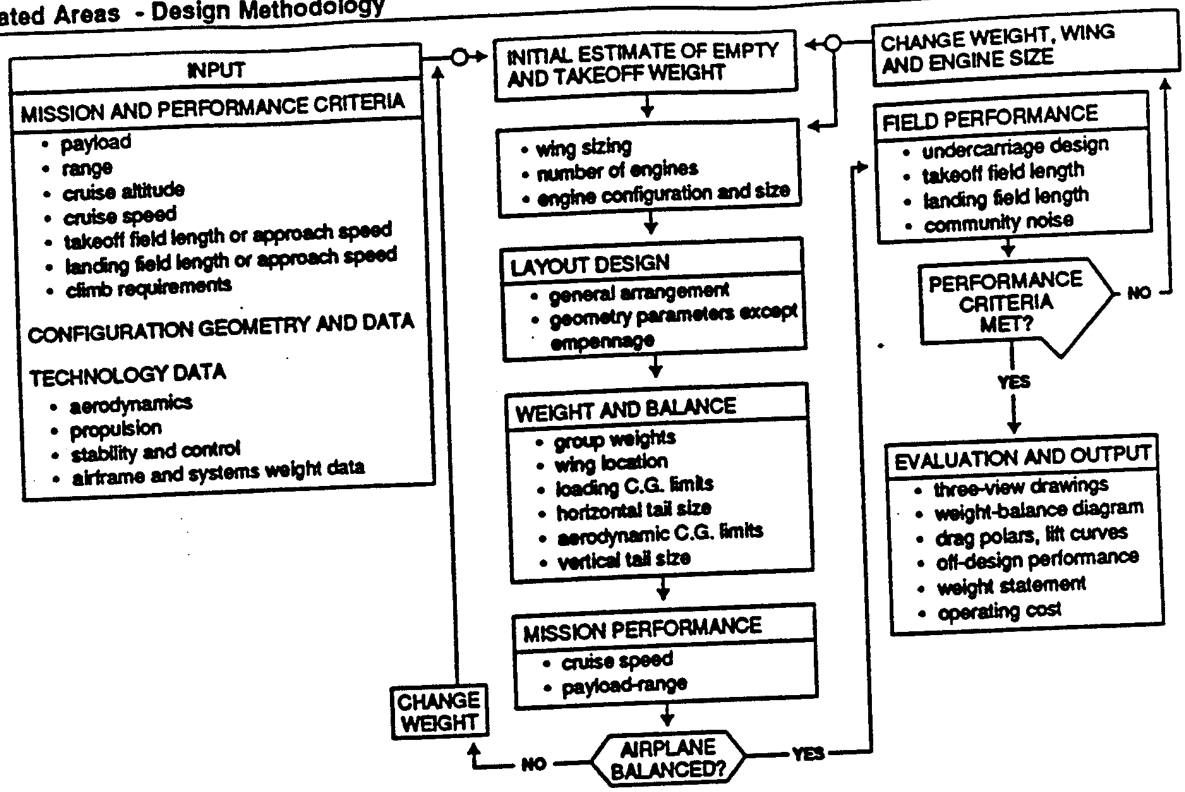


Figure 4-4 — Example of a generalized design procedure

Importantly the configuration concept is selected early in the process to (hopefully) avoid wasting valuable time and effort on unproductive approaches. When applied to wingships risk occurs in early configuration concept selection. There is the possibility of selecting a configuration type, that (when optimized) does not perform as well as an alternative. In the aircraft case, and possibly in the wingship case, the configuration is mostly driven directly by the specifications and requirements, and configuration does not have a strong influence on the utility function. Such things as payload shape, provisions for loading and unloading, pilot visibility, antenna apertures, access to engines, foreign object damage and etc. generally determine the configuration type.

4.1.3 Tentative Wingship - Specific Design Method

Figure 4-5 is a design method for wingships adapted from the airplane examples described above. We have had enough experience with this design loop to know that it can converge for many practical cases. We used a design loop similar to this one to generate parametrics in the Wingship Investigation Final Report.

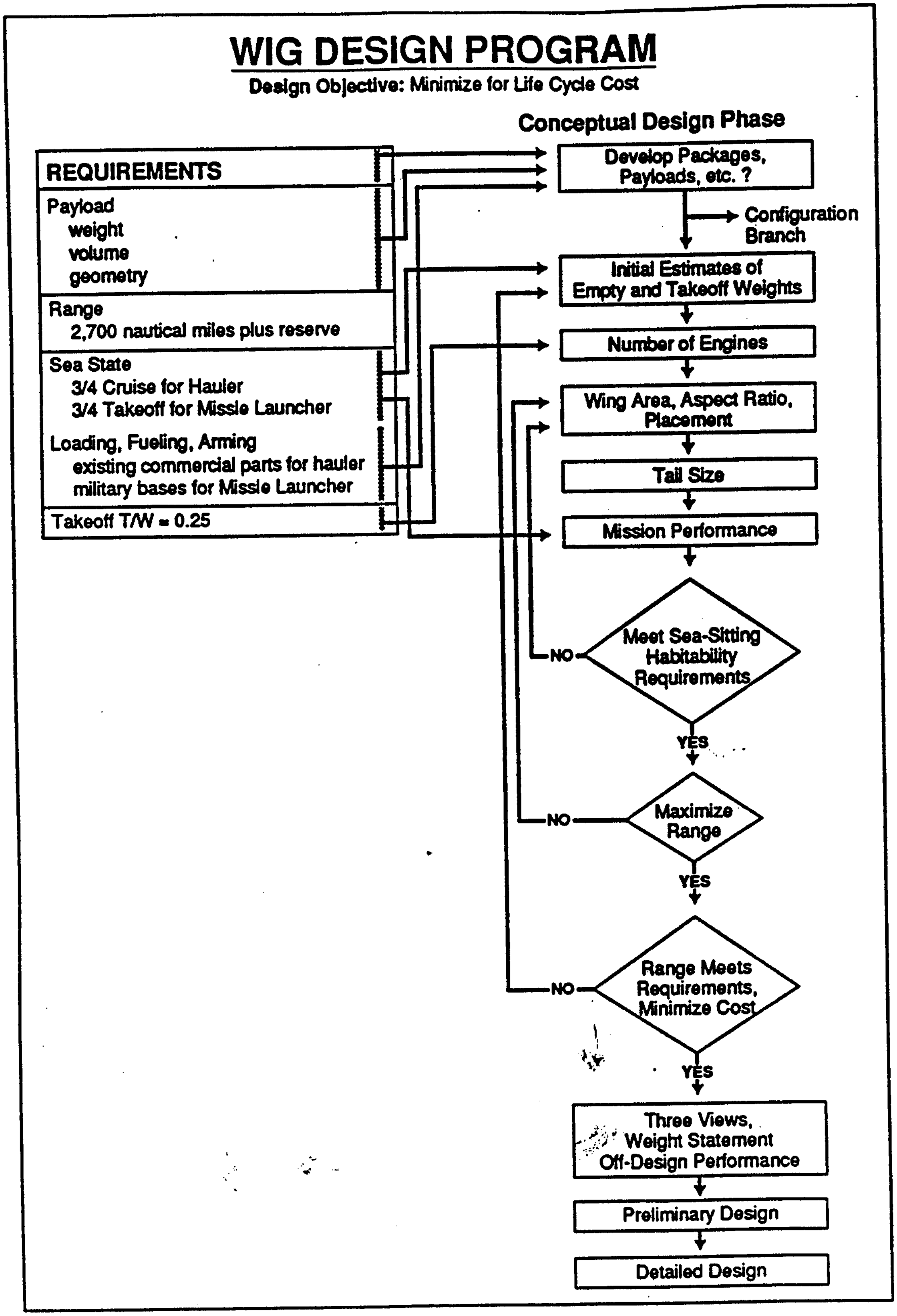


Figure 4-5 — WIG Design Program

4.1.4 Deficiencies

The candidate design method just described may be adequate but it is not presently possible to show that it is best or that it will converge for a wide range of requirements and constraints. No assurance can be made that there are not more efficient methods. Further, specifically for wingship applications, the necessity to narrow the configuration early may be undesirable. How undesirable depends critically on requirements and constraints. For example, the height of the VLS system for the combatant wingship is such that it could not be carried in any reasonably sized flying wing. The flying wing configuration can reasonably be rejected at the outset. However, an all wing configuration might be practical for a large passenger carrier with no specific payload configuration requirements .

4.1.5 Methodology Development Required

The systematic development of a wingship-specific design method requires analysis of the cross sensitivities of key design features. Also required is some systematic way of defining and sorting the configurational possibilities for diverse mission types to avoid the necessity of carrying multiple configurations through the constrained optimization process.

Steward, a systems engineering book (Reference 1), suggests a comprehensive design method for the feedback loops in a design process to optimize the process itself. This method, or an equivalent, should be applied to the wingship design problem to systematically derive an efficient design methodology.

The configuration selection issue is more subtle.

4.2 Flight Testing

4.2.1 Goals and Objectives

According to DoD Instruction 5000.2 "(t)est and evaluation programs shall be structured to:

1. Provide essential information for assessment of acquisition risk and for decision making;
2. Verify attainment of technical performance specifications and objectives;
3. Verify that systems are operationally effective and suitable for intended use; and,
4. Provide essential information is support of decision making."

The flight test program for wingship investigation will be a tailored mix of developmental and non-developmental component, system and vehicle testing designed to provide flight evaluation and certification of new technology applications. Much of the testing will use dedicated testbed vehicles chosen for their suitability, flexibility and affordability, since any "new design" wingship testing will have to follow development and testing of engines, sensors, structures and other related systems. Two candidates testbeds are the American *Flaircraft* five-seater and the Russian *Spasatel* under construction in Nizhny Novgorod. Ground test (wind tunnel, tow tank and etc.) data and flight simulation data will be integrated into a flight test database containing available Russian flight test data, which will continue to grow throughout the flight test program. To provide a structured approach to testing, an abbreviated Test and Evaluation Master Plan (TEMP) must be developed. This document will be the controlling license for the flight test program, and as such must be reviewed and approved on a regular basis.

Flight testing will be done on sub-scale and full-scale test articles, and will address parameter identification (PID), flying qualities and performance (FQ&P) and other basic issues to evaluate the ability of wingship designs to meet requirements or specifications. Test articles will be instrumented to collect required data which will be reduced, analyzed and added to the database. Various integration and installation approaches for components and systems will be tested as required, as will different vehicle configurations.

The primary goal of the flight test program is collection of sufficient valid data to assess specification or requirement compliance, and provide relative indexes of merit for competing system or design candidates. Secondary goals are identification of potential operational and technical limitations of alternative concepts and design options, identification of cost-performance tradeoffs, and identification of design risks. Test planning, data point determination, pass/fail criteria development and data collection methodology all play important parts in the realization of these goals.

4.2.2 Scope

The flight test program will address all testing including:

- Full-Scale Testing - This is the testing of production hardware or full size replicas. Actual hardware is tested for form, fit and function while full-scale models are tested for form and fit (although limited functionality may be ascertained, such as in the case of drop models).
- Sub-Scale Testing - This is the testing of reduced size replicas for function. Some examples of sub-scale testing are wind tunnel tests or tow tank tests. Sub-scale models may also be used for free-stream (air or water) testing when mounted on a testbed aircraft or boat.

- **System Testing** - This is the end-to-end testing of systems functionality ranging from breadboard through brassboard to production representative hardware. Whether conducted on a bench, on a testbed or integrated into a test article, system performance measurement is the objective.
- **Component Testing** - This is the lowest level of testing. Individual components are tested for form, fit and function prior to integration into systems. Most of the "ilities" testing (reliability, maintainability, etc.) is done at this level.

4.2.3 Test Planning

The key to success in testing is thorough test planning. Taking pains to identify critical issues, possible anomalies and potential outcomes prior to drafting test procedures results in more efficient and effective testing. This is especially true for the wingship investigation because of the high costs associated with operating a large vehicle such as *Spasatel*.

At a minimum, test plans prepared for wingship testing must consider:

- **Purpose of Test** - What is the test team trying to achieve? What portion of the specification is being addressed? What is the impact of not conducting this test? Where does this test fit into the TEMP schedule?
- **Data Requirements and Validity** - What data must be collected to measure performance? What data can be collected during the conduct of the test? How much data is sufficient? What are the conditions which would cause the data not to be valid? What modeling/simulation data are available for predicting flight data result ranges?
- **Asset Requirements** - What test articles are required? What configuration? What instrumentation? What supporting assets?
- **Test Conduct** - How will the test be conducted? Who will be responsible for what? How will the test be designed to afford the maximum possible opportunities to capture all required data points? What external interfaces must be considered? What special safety precautions must be observed? What can be accomplished if equipment becomes degraded prior to test completion?
- **Data Collection, Reduction and Analysis** - What method will be used by whom to collect data? What outside influences must be considered? What secondary/backup system can be employed? What data are required in real time; what can be delivered later? Who will perform data reduction; how? What assets are required for data reduction? Who will analyze data? In what format will results be compiled? How much data can be shared between test events? How will supporting data from other tests be used to verify results? What measures of effectiveness (MOEs) need to be developed? Who will ensure all collected data are added to the database?
- **Pass/Fail Criteria** - What constitutes pass, conditional pass or fail results for each event? What factors might influence data? At what point is it no longer desirable to continue the test (exit criteria)?

4.2.4 Test Articles

As stated above dedicated testbed platforms are required in this test program, since no mission-designed wingship will be available for collecting the data required for designing new wingships. Two currently available vehicles are being considered for this role. Bill Russell's *Flaircraft* is a small ram-wing craft descended from the Alexander Lippisch/Rhein-Flugzeugbau designs of the 1960s and '70s. It is constructed of molded fiberglass reinforced plastic (FRP) and powered by a completely off-the-shelf (COTS) internal combustion gasoline engine turning a fixed-pitch pusher propeller. The outer wing panels

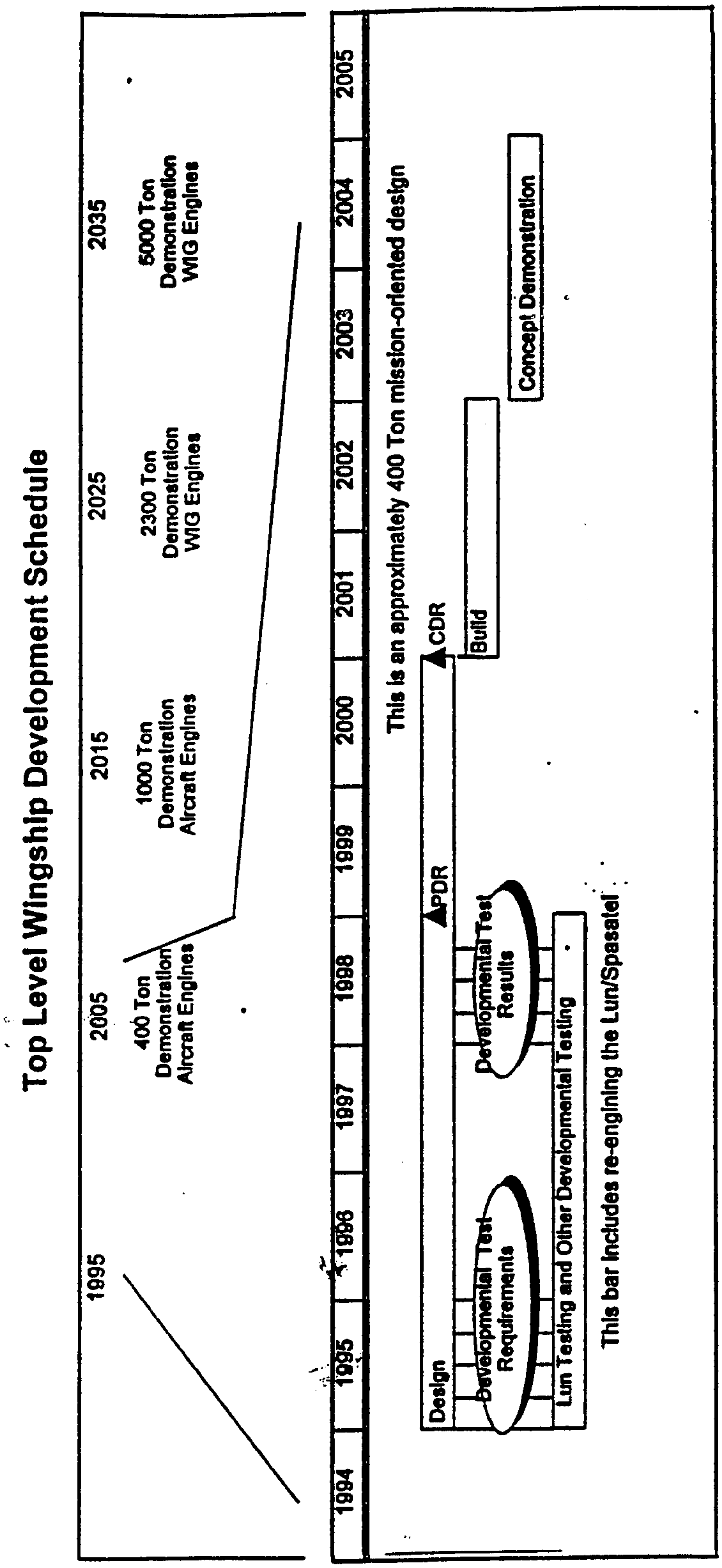


Figure 5-1 - Top Level Wingship Development Schedule

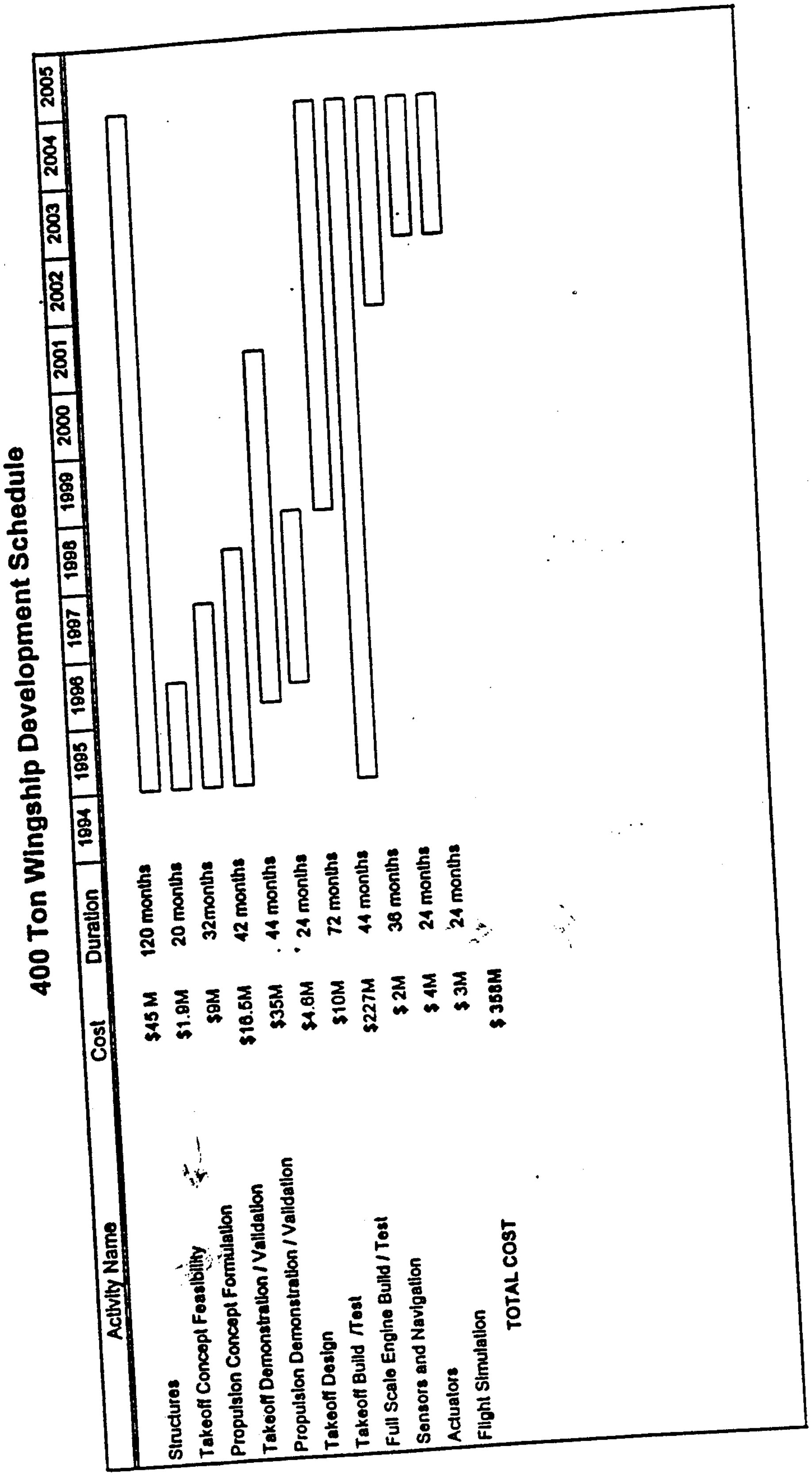


Figure 5-2 - 400-Ton Wingship Development Schedule

Appendix A - Takeoff Technology

Power Augmented Ram (PAR): Limitations of Expected Improvement

In order to estimate the best perfomance possible when using power augmented ram (PAR) we developed a plot of non-dimensionalized altitude (h/c) versus non-dimensionalized thrust (T_G/W) at various loadings (K_2) for three differenct length-to-beam ratios (L/b). These plots are presented in the Section 3.1.1 Takeoff and Landing Technology Section of this report. This appendix presents how each parameter h/c, T_G/W and K_2 is derived.

The excess thrust of a PAR system must provide some margin over the drag.

Drag defined as:

$$\frac{D}{W} = 2R_c\left(\frac{W}{\gamma cS}\right) \qquad (1)$$

$$\frac{W}{\gamma cS} = K_2 \qquad (2)$$

$$\frac{D}{W} = 2R_cK_2 \qquad (3)$$

R_c	=	Wave Drag Coefficient
D	=	Drag (LBF)
W	=	Weight of Loaded Vehicle (LBF)
γ	=	Density of Water (lb/ft^3)
c	=	Wing Chord—Length of Cushion (ft)
S	=	Wing Area of Cushion Area (ft^2)
K_2	=	Davidson K_2 Parameter

R_c is a resistance factor which is a function of the L/b ratio of the vehicle area effected by PAR. To determine the thrust required for takeoff, we are interested in the maximum value for each L/b ratio.

In our analysis we have plotted non-dimensionalized thrust for three different L/b values of 0.2, 2.0 and 10.0. The R_c values at these L/b values are 1.95, 1.08 and 0.58 respectively. The R_c value for L/b=10 was estimated by extrapolating the data from Figure A-1.

Equation 3 was developed by L. J. Doctors (Reference 1). Figures A-1 and A-2 are plots of the Wave Drag Coefficient R_c, (also referred to as Wave Resistance Coefficient) versus the Froude Number. Figure A-1 is from Reference 1. Figure 2 was developed for smaller L/b values using the formulas from Reference 1.

Equations 1, 2, and 3 relate drag to load. We now need to evaluate thrust and include the effect of PAR on thrust.

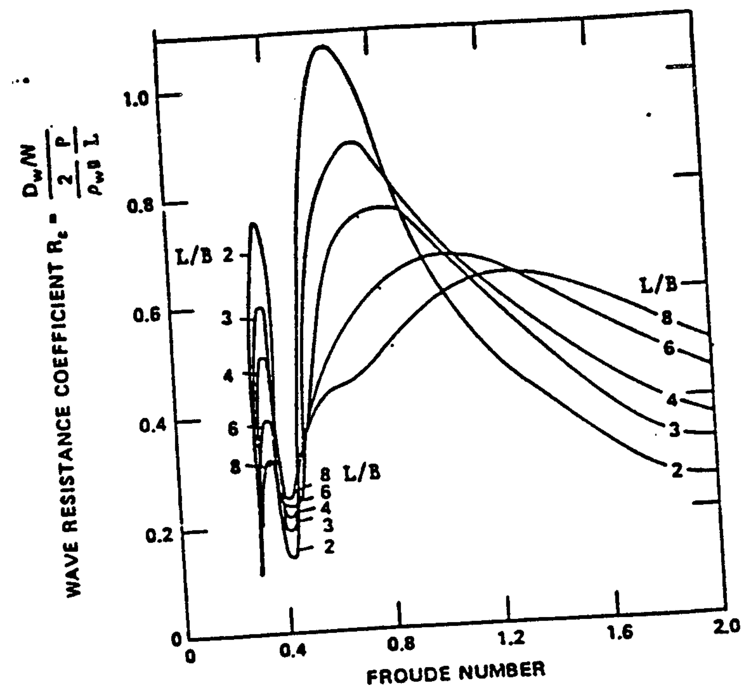


Figure A-1 - Doctors' Wave Resistance Coefficient

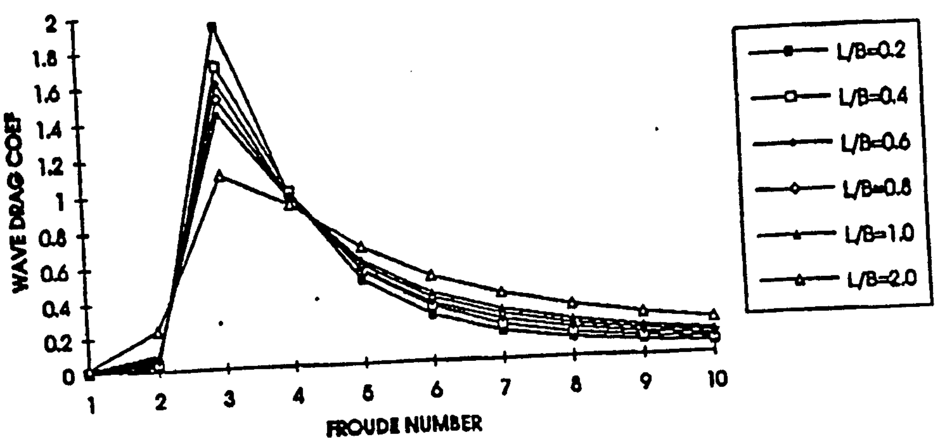


Figure A-2 - Wave Drag Coefficient for Small L/b Values

$$\frac{T_N}{W} = Acceleration + \frac{D}{W} \tag{4}$$

$$\frac{T_G}{W} = \frac{1}{C_T}\left(\frac{T_N}{W}\right) \tag{5}$$

$$C_T = 2\frac{t_2}{t_1} - 1 \tag{6}$$

$$\frac{t_2}{t_1} = \frac{4\frac{t_2}{h}}{1 + 2\frac{t_2}{h} + \left(\frac{t_2}{h}\right)^2} \tag{7}$$

$$\frac{h}{t_1} = \frac{t_2 / t_1}{t_2 / h} \tag{8}$$

$$C_p = 1 - \left(\frac{t_2}{h}\right)^2 \tag{9}$$

T_N	=	Net Thrust (LBF)
T_G	=	Gross Thrust (LBF)
C_T	=	Thrust Coefficient
t_1	=	Thickness of Incoming Jet
t_2	=	Trailing Edge Gap
h	=	Distance Between Wing and Water
C_p	=	Pressure Coefficient

From Reference 2 we get the definition of both the thrust coefficient and pressure coefficient in terms of vehicle parameters and vehicle altitude (h) when PAR is used in the vehicle design.

Figure 3 is a picture of a power augmented ram wing from Reference 2. In our analysis we assume that ß is -180°, which means that the engine exhaust is deflected 180° off the leading edge of the wing.

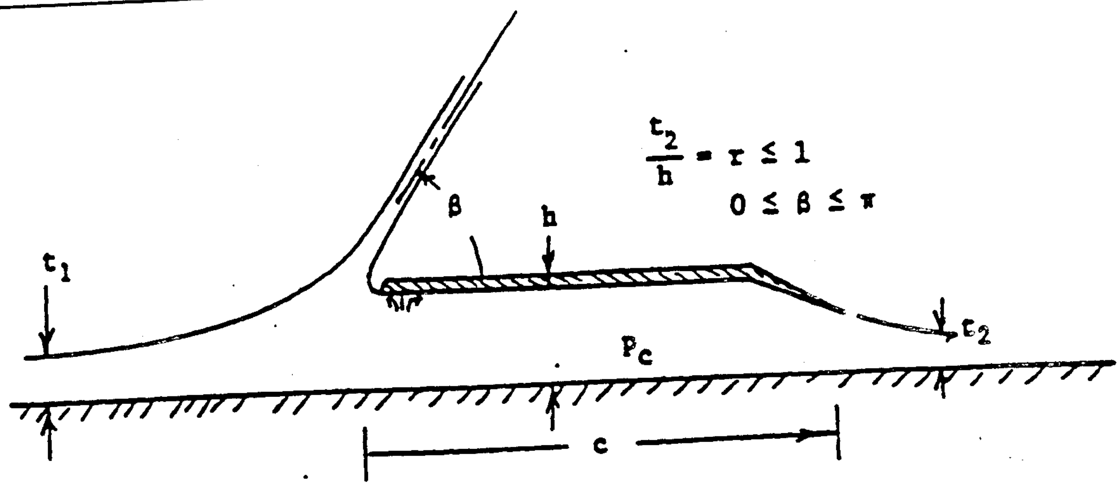


Figure A-3 - Power Augmented Ram Wing

Our plot uses K_2 the vehicle loading parameter; $\frac{T_G}{W}$ the vehicle thrust parameter; and , $\frac{h}{c}$ the vehicle altitude parameter. Using algebraic manipulation, we derive an equation for $\frac{h}{c}$

$$\frac{t_1}{c} = \frac{T_G C_P}{w2} \tag{10}$$

$$\frac{h}{c} = \left(\frac{t_1}{c}\right)\left(\frac{h}{t_1}\right) \tag{11}$$

We then use a computer program to generate the graphs.

Derivation of K_2 Value and Length/Beam Ratio

Russian Vehicle Parameters (Data from Reference 3)

$$K_2 = \frac{W}{\gamma CS}$$

W = Total Gross Weight of the Vehicle = 308,000 lbs (Reference 3, Page 13)

C = Wing Chord or Boat Length

S = Wing Area (area of cashion) or Hull Area

Based on data from Figure 140 (Reference 3, Page 37)

Wing Area for Russian Vehicle (S)

1. Calculate Area of Large Rectangular Planform

$$\frac{(60.96in)(20)\times(15.36in)(20)}{144\frac{in^2}{ft^2}} = 2{,}600.96ft^2$$

2. Calculate Area of Triangular Portion of Wing

$$\frac{\frac{1}{2}\left[(20)\left(\frac{60.96-7.86}{2}\right)\times 20(23.22-15.36)\right]}{144\frac{in^2}{ft^2}} = 289.84ft^2$$

Multiply by 2 for both wings

3. Calculate rectangular area of hull between triangular portions of wings

$$\frac{(20)(7.86in)\times(23.22-15.36)(20)}{144\frac{in^2}{ft^2}} = 171.61ft^2$$

Total area = $2{,}600.96ft^2 + 2(289.84ft^2) + 171.61ft^2 = 3{,}352.25ft^2$

Wing Chord of Russian Vehicle (C)

$$c = \frac{\text{Wing Area}}{\text{Span}} = \frac{3{,}352.25\text{ft}^2}{\frac{(20)(60.96)}{12}\text{ft}} = 32.99\text{ft}$$

$$K_2 \qquad \frac{308{,}000\ \text{lb}}{\left(62.4\frac{\text{lb}}{\text{ft}^3}\right)(32.99\ \text{ft})(3{,}352.25\ \text{ft}^2)} = 0.044$$

$$L/b \qquad \frac{L = \text{wing chord}}{b = \text{wing span}} = \left[\frac{32.99}{\frac{(20)(60.96)}{12}}\right] = 0.32$$

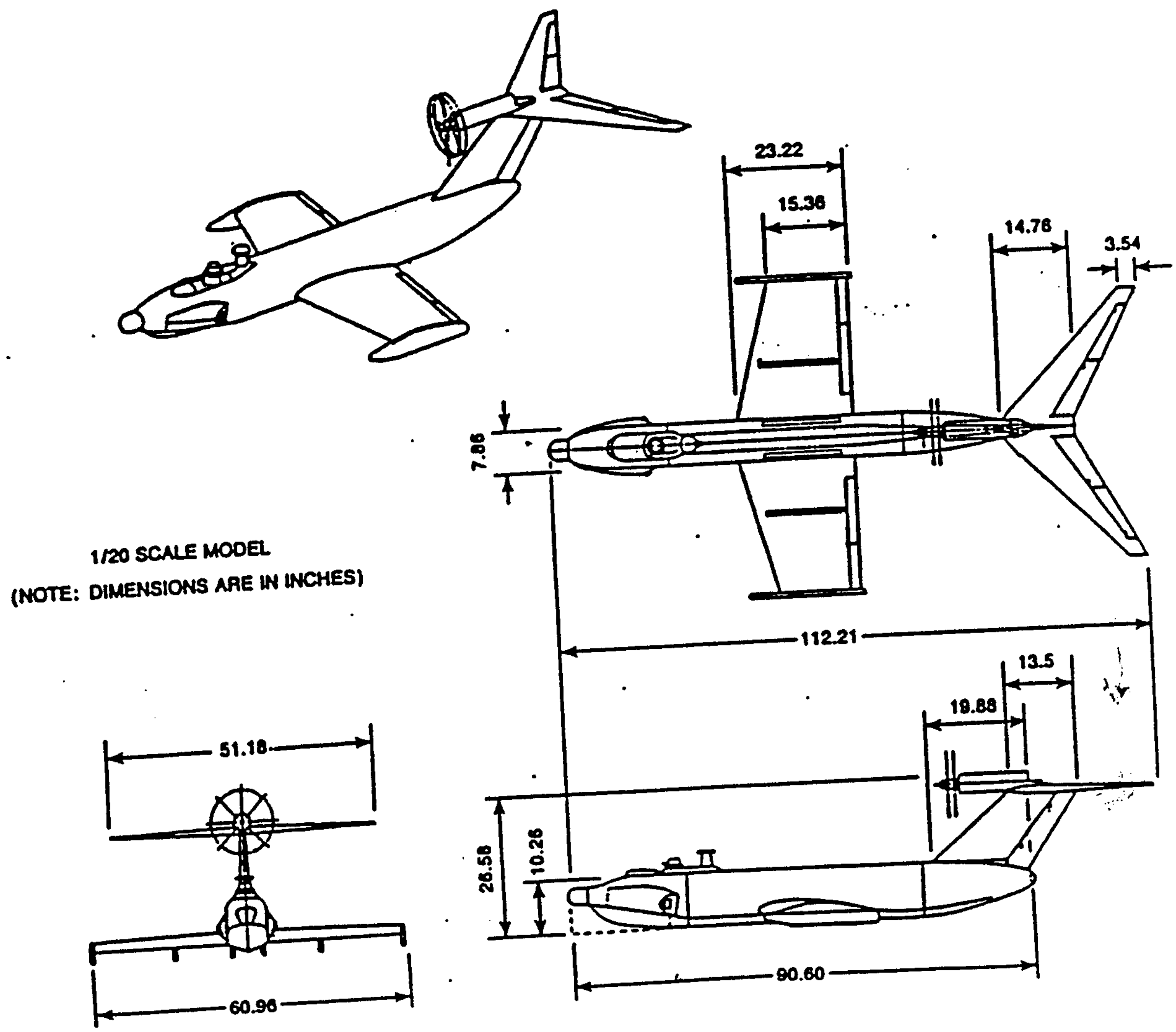


Figure A-4 - 1/20 Scaled Model of Russian Orlan WIG Vehicle

References

1. Doctors, L.J. "The Wave Reistance of an Air Cushioned Vehicle," Thesis, University of Michigan, 1970.
2. Gallington, Roger W., "Sudden Deceleration of a Free Jet at the Entrance of a Channel," Report ASED 350, Jan 1976.
3. Bry, Cmdr William A..., Robert L. Walker, And Gary R. Smith, "An Analysis of the Performance and Stability Characteristics of PAR-WIG," CRDKNWC/RD-33-93/99, Carderock Division Naval Surface Warfare Center, Bethesda, MD, April 1993

Appendix B • Propulsion System

Details of Taxi/TATO Systems - Noise Abatement/Take-off Assist

At this time, the preferred consideration for beach noise is to move the vehicle away from the area, meaning taxi it out to sea and back, probably 5 to 10 NM on takeoff and possibly even the same after landing. The main propulsion engines are not to be used for this purpose because of their high fuel consumption. The Taxi/TATO section below gives strong indications that the taxi speed should be about 15-20 knots and several 501K engines could make large fuel weight savings for 10-20 NM taxi lengths/flight. These were worth 14-17% of mission fuel that could be used for range, or cargo. These marine propulsors should also be considered for in-flight vehicle systems electrical power, plus pneumatic and hydraulic power because of their good sfc (up to 20% better than APU gas turbines which the Russians use), their demonstrated excellent reliability, and existing resistance to salt sprays and shock from wave impacts. (The three 501K marine propulsion/TATO units makes more power than the Russian NK12 turboprop and perhaps should be considered as a source of air propulsion once in flight — which has not been done. It is to be noted that the 501K drive could be to a generator with an electric motor located in the stem driving the screws. This would permit the power sections to be located wherever the balance needed them to be plus would permit electric drives on most accessories on the aircraft, which is now a trend of interest on both ships and planes. However, both the reduction gear box (RGB) and the generator/motors would have to be lightened substantially. The RGB weighs 3798 lbs but the blast hardened generator weighs 25,900 lbs. If this could not be done, the drive to the jet pump/screws would have to be direct through a transmission as it is now on the hydrofoil boat.

On 5/26/94, Allison's Darrel Rains (317-230-4555) advised that another T56/501 derivative which may have superb application to "TATO" is their "KF" series. This is a 501 engine with a power turbine arrangement that is used to direct drive a jet pump for propulsion on the Boeing Jet Foil boat (a hydrofoil) near Hong Kong. (See information package from Allison on this commercially available package.) The power section unit (sans jet pump) weighs 2500 lbs and has a maximum output of 5425 HP. The attractiveness here is that this is the engine type and size desired, and it has already been matched out with a jet pump for an application very much like the WIG.

Possible Taxi engines - On-board shaft drive T56/501K gas turbines are a consideration for mitigating the takeoff noise problem by moving the WIG away from the beach so the takeoff noise of 4 to 8 large engines will go unheard. Such auxiliary engines driving screws or even jet pumps, rather than using the main propulsion units, are a technique for large savings on taxi fuel that can amount to 17% of mission fuel and range. The savings result from the fact that the vehicle taxi speed is very low which requires high turbofan thrust (and fuel flow) values to generate the HP to drive the hull. Preliminary investigation using Reference 1 data (see Figure 1) suggests the following schedule for power and fuel flows to drive a 60 meter water line length hull (with the wings out of the water) as a function of water speed:

Speed Knots	Speed/length ratio. $V/(L)^{0.5}$	HP Ton	HP	Hull Drag, Lbs	Wf Screws PPH	Wf Fans PPH
10	1.21	3	1200	39100	600	12510
15	1.81	13	5200	112954	2600	36145
20	2.41	24	9600	156398	4800	50047

The assumptions for the marine propulsion unit were:

- SFC = 0.4 PPH/HP for diesel (table above)
- SFC = 0.52 PPH/HP for T56 (following tables)
- gearbox and screw efficiency = 0.8, use 0.6 for jet pumps
- screw = this might also be a jet pump, particularly if the marine unit was used to assist in takeoff thrust

The assumptions for the turbofans were:

- SFC = 0.32 PPH/Lb Thrust

The turbofan SFC is typical of new vintage commercial engines between cruise and maximum power at SLS. The SFC for the powerplant driving the marine propulsion unit is typical of good diesels. If a power section from a turboprop gas turbine, such as the T56 Series III engines, was used it's SFC would be on the order of 0.52, about 30% more than the values shown in the preceding table.

The above table suggests very strongly that how far and how fast the WIG must taxi for takeoff will have a large effect upon fuel flow rate and power required in the engines driving the marine propulsion unit - screws or jet pumps, etc. It may be important in dealing with the one-engine out takeoff requirement to notice that at the mid to high end of the takeoff speed range a jet pump may be more effective than a propeller.

High speed, aluminum, 4-stroke, supercharged, marine diesels are believed available (USN Airship program) but a reduction gearbox would be required. The USN YEZ-2A airship uses two such Italian CRM 18D/SS, 1850 hp at 2100 RPM, diesels. They have 18 cylinders in 3 banks of 6 each, 3.08 liter displacement/cylinder for a total displacement of 55.4 liters, CPR = 16.25:1, weight of 3745 lbs, which is light for a diesel. Although 1 diesel could do the 10 knot case, it would require 3 for 15 knots, 5 for 20 knots.

It should be noted that the Airship program is presently very modestly supported by ARPA (Tom Swarz), and has champions within NAVSEA (who may be a funding source in late 94/95) and NAWCAD/WARM. The CRM diesels are considered production equipment, they are available and equipment includes heat exchangers modified from water/water to water/air for a vehicle that seldom exceeds 80 knots. Westinghouse in the US is responsible for the overall vehicle program, and would probably be pleased to discuss another Naval application.

As far as the gas turbine engine for the marine propulsion unit drive concept is concerned, the T56/501 engine is an excellent contender. The USN has bought most of the 15,240 T56s built between 1956 and January 1993. Many of these are marinized versions known as the 501-K17 which power a reduction gear box/generator set turning at 1800 RPM for remote electric drives on Navy DD 963's. The early or Series I

T56 had an output of about 3700 HP. The most recent or Series IV (T56-A-427) has an output of 5600 HP, flat rated out to 86° F. The 501K-34 uses the same hot section as the 427. All T56s through Series III have a power section constant shaft speed of 14,300 RPM. The Series IV has about 4% more input RPM to the RGB and substantially less surge margin than the old compressor which was used on Series I, II and III engines. The aircraft version, the T56, employs a reduction gearbox (RGB) which has an output shaft speed of about 1100 RPM. Each power section weighs 1825-1885 lbs. The weight of the aircraft RGB is 550 lbs. The T56 power section plus RGB weight is 2435 lbs. One very distinct advantage of the 501K is that this engine has already been marinized for NAVSEA application to driving shipboard generators. Possibly of equal importance is the fact that the 501K has been successfully tested and qualified under high (19) g loads simulating nearby underwater explosions, such as mines or depth charges. From conversations with the Russians, it is believed that the possibility of high g's (8 to maybe 10) from impact with waves at flight speeds is real. Engine bearing damage was their result which required removal of all engines when the craft landed. Hopefully, the 501K would tolerate such mishaps better and still be able to provide propulsion service when on the water. These features plus the ability to operate on Naval distillate fuel (diesel fuel) would transfer very easily to WIGs. Applied to the above problem, one T56/501 could push the 400 ton WIG along at about 15 knots and two in a "twin pack" could accommodate about 20 knots. The 501K-17 is rated at 4300 HP at 60° F and the 501K-34 is rated at 5300 HP.

The following table compares the weight of the marine propulsion unit engines (direct drive, not generator electric) and their fuel against just the fuel weight burned if the canard mounted large turbofans must be used for a 10 or 20 mile taxi of the 400 ton WIG.

10 NM Taxi Propulsion Weight Allowances

Hull Speed, Knots	Turbofan fuel, Lbs	Diesels + fuel, Lbs	T56s + fuel, Lbs
10	12510	4345	3165 (1 T56)
15	24096	12968	4638 (2 T56)
20	25024	21125	7890 (2 T56)

20 NM Taxi Propulsion Weight Allowances

Hull Speed, Knots	Turbofan fuel, Lbs	Diesels + fuel, Lbs	T56s + fuel, Lbs
10	25020	4945	3945
15	48192	14701	6891
20	50047	23525	11010

Both tables show that a marine propulsion unit that pushes on water instead of air may produce a substantial fuel/weight savings over using the main propulsion turbofans for a long taxi period. However, each type of marine taxi engine has some strong speed or range effects.

For example, if a slow 10 knot taxi speed could be tolerated, the single T56 is technically superior but the lower cost single diesel needs a weight allowance that is only 1100 lbs more. Either diesel or gas turbine is lighter than using the turbofans by factors of 3 to 4:1 if the taxi distance is at least 10 or 20 NM. The fuel weight savings is 8200 to 9400 lbs - which for a 30% fuel fraction on-board is about 4% of mission fuel. Success in this slow speed scheme would likely be if the taxi distances were 10 miles or more. For short runs, like 3 miles or less, the weight allowance for the diesel and its fuel is about equal to or greater than the

weight of fuel burned by the large turbofans. This means that for very short taxi runs the concept of a taxi engine is not weight effective - however it is still very noise effective, which is what is driving the problem. Slow taxi speeds like this however seem very unlikely owing to the need to fight currents and waves and maintain some reasonable headway and steerage in unfavorable sea states.

At 15 knots, even with 3 diesels, the total taxi allowance is still lighter than for the turbofans by factors of 2 to nearly 4:1. Using the T56, the weight savings is a factor of 5 to 7:1 over the turbofans. For a full 20 nautical mile taxi on one mission, the fuel savings with the single T56 would be very large - about 41,000 lbs of fuel, or 17% of the mission fuel which could now go for range. At 15 knots the T56 is the very clear cut winner as long as each taxi is over 2 miles.

At 20 knots, the turbofans are still the heaviest means of taxi but they are not substantially worse than 5 diesels for a 10 NM run. However, again the weight penalty for the T56 (this time in a "twin pack") is much lighter than the taxi fuel penalty for the turbofans by factors of roughly 3 to 5:1. The fuel savings on a full 20 NM taxi run would be about 39,000 lbs - almost the same as on the 15 Kt run for 20 NM and worth 17% in mission fuel and range. At 20 knots, the T56 is also the clear cut winner, again as long as the taxi is longer than about 2 miles. If a three engined TATO unit were to be used, with a weight of 12,000 lbs, the fuel burned would still be almost as above for taxi, yielding a maximum total weight of 12,000 + 5920 = 17,920 lbs, which is still a large fuel savings over the big turbofans by nearly 32,000 lbs, or about 14% of mission fuel.

The unexpected factor in the above was the clear effect of taxi length upon the ability of the marine propulsion units to save weight. The message being that if the WIG does not have to travel more than about 2 miles total from the dock to the takeoff point, there is little weight reduction in using this scheme to reduce perceived takeoff noise. For taxi lengths under 2 miles, from strictly a weight consideration, the WIG could just as well "bump along" at 15 to 20 knots making 110 -160,000 lbs of thrust (and about 104 -107 dB) on its large turbofans. However, noise restrictions will likely dominate in the US and any locomotion within earshot of the harbor or the beaches will be via some quieter marine propulsion unit inside the WIG. The WIG designer will thus be made to keep taxi quiet and fuel efficient whether he wishes to or not.

One-engine out takeoff requirement - To meet this requirement with just the main or air propulsion engines means that 266,500 lbs of thrust must be carried with 4 engines rated at 66,500 lbs thrust each. The takeoff T/W requirement of 0.25 only needs 200,000 lbs of thrust but this must be met with one engine out. Considering that WIGs have the problem of excess thrust available at cruise anyway, the extra engine is not an attractive solution, even if it is how the problem is met in today's aircraft. Another solution might be via three on board taxi gas turbines rated at about 5425 HP each (16,275 HP in total). Each engine unit with power turbine and exhaust collector box weighs 2500 lbs. Allowing 1500 lbs for each jet pump and drive places a three engine unit at 12,000 lbs. This is about 2000 lbs more than a large turbofan but they also accomplish taxi and have no external drag.

At 40 knots and a power transmission plus assumed jet pump power conversion efficiency of 0.6, a three engined unit would generate 79543 lbs of thrust. This could be the added engine needed for the one engine out assist - if the problem of getting the power to the water medium can be handled.

Props at high water speeds approaching liftoff would tend to operate with much of their blades out of the water which produces a rooster tail that would in turn tend to damage the WIG skin plus their efficiency is probably low. A better approach might be the use of jet pumps which need intake and output water ducts

but have better efficiency than marine screws at high water speeds. (Gallington conversation with Lister on 5/26/94).

Assessing TATO feasibility/impact upon engine sizing/selection -the first step would be to determine whether TATO could be done or not in order to accomplish two objectives:

1. to provide quiet taxi power out to 20 knots, probably to 80-90 dB at dockside (90 is the 8 hour exposure limit on industrial noise) and
2. to provide enough thrust via water propulsion during the takeoff run to be assured of a safe takeoff even with one main air propulsion engine out during takeoff. This may be the equivalent of still being able to effect safe takeoff even though the T/W with all main engines running at full augmented thrust is no more than 0.25.

To assess this, the first step is to gather enough information to better define the installation and performance characteristics of the Allison 501 KF and jet pump package from zero to takeoff speed. The next step would be to size the air propulsion engines so that the sum of their thrust with one engine out and the TATO package yields not less than 0.25 T/W. (In fact this would be the guideline no matter what the takeoff thrust boost plan was.) Assuming success and that TATO could basically downsize the air propulsion thrust enough to relieve them of the one engine out requirement, the next step would be to proceed into the engine selection process below (with one big exception) and to start work on ensuring that the TATO concept can indeed be managed so it does not burn up when the WIG leaves the water. The exception referred to here is that the number of newer US engines that will fit the TATO concept at 400 tons are few. The PW2037 is the only one found (38,250 lbs), unless it develops that the amount of downrating needed to accommodate salt ingestion on one flight is so extensive that an engine in the 50,000 lb thrust class must be used as a starting point. At any rate, for a 400 ton WIG, if TATO appears as a likely success and a 38,250 lb engine is needed, the PW2037 is the only one today that seems applicable. If nothing changes, that engine should be the one used in the salt tests as defined below.

<u>RDT&E of Marine propulsion units (the T56/501K/570K)</u> - Initially, either analysis or model testing in a tow tank of the WIG hull should be done to assess power requirements for the hull at 10 - 20 knots with some emphasis upon whether the wing is in the water or not. A good candidate for test and evaluation would be the complete drive system between the T56(s), the screws or jet pumps and the accessories normally driven by either the main engines, or APUs as the Russian WIGs do. This would include electrical generators, hydraulic pumps, air conditioning/environmental control unit and the air compressors for driving all four engine starters simultaneously and powering the water wash equipment. The level of development on these items would likely be engineering development, 6.4. However, if the weight of the power transmission system and jet pumps is high, some 6.2 or 6.3 effort may be appropriate to get aviation weights into what has previously been marine technology.

Vehicle noise T&E - Regarding noise, one part of the effort should be to simply document the noise of the engines on the vehicle and as modified for WIG operations, including the augmentor. Since the basic information is best done on the vehicle, look to the vehicle test and evaluation plan for definition. This should also include the T56s running inside the hull. The issue to be answered here is how far out to sea must a 400 ton WIG go before takeoff will not violate beach noise levels. If taxi distances can be short (about 2 miles) the development effort should anticipate pressure to find ways to get out of the beach area quietly on the main engines, increasing speed as they go. The purpose of that exercise will be to try to eliminate the complexity of separate marine propulsion units. However, some form of large APU type

power unit will be required for both in-flight power and post landing water washing. Consequently, it is probably best to integrate all those requirements into one efficient prime mover, like a T56. Moreover, the effects of taxi length upon fuel burned will be small once the decision is made to use T56 powered marine units located inside the hull.

Obviously, there must be a survey to determine what some of the communities on the East and West coasts and the Gulf of Mexico will tolerate regarding noise. A report should be published and made publicly releasable that defines WIG takeoff noise as a function of distance from the listener and also identifies what the acceptable noise signatures are for various US coastal communities where WIGs might operate from. Some appropriate time period should be allowed for these communities to review such information and make their comments available to DoD. If further mitigating action is required beyond taxiing 10 miles out to sea to avoid being a noise nuisance, then DoD will have to take that under advisement before it begins it's first batch of full scale tests at 400 tons. (Points of contact on this are: EPA, Karen Metchis, 202-233-9193 and DoD, Bill Goins, 703-756-5640. On 5/27/94, Karen advised that minimum times might be on the order of 30 days and that EPA General Counsel should be contacted, Laurie Schmidt, 202-260-5327).

The key elements in the above approach are:

- early identification of a likely problem (beach noise)
- early identification of a likely solution (taxi out to sea)
- early identification of a design solution (taxi engine)
- early use of test data to report actual noise to public
- willingness to use public comments for DoD planning
- willingness to adjust operations to suit needs of communities

High temperature environment for wing/fuel tanks. This is a needed item for propulsion if an augmentor and PAR are used with vectored thrust. The Russians desire the approach of an augmentor (using mixed flow turbofans) but are being thwarted at about 10% augmentation by concerns for under wing blowing (PAR) exceeding the hot surface self ignition temperature for conventional jet fuel at augmentation temperatures of 425° F. Adequate augmentation of the fan stream will require avoiding both a structural problem in a hot wing and any fire or explosion hazard in the wing tanks. The augmentor will likely be on for two to three minutes maximum, which identifies it as a transient problem for fuel tanks and structures. Underwing blowing for PAR with a 40% augmented fan stream may not be feasible unless these two other vehicle capabilities exist. [Note: A source of design information on this topic might be Lockheed Burbank who developed the SR-71. One of their major and continuing in-service problems was wing tank leakage with "only" 600° F stagnation temperatures and a very elaborate system of sealants and special titanium part attachment/fastener schemes for the JP-7 fuel. While JP-7 has a normal JP flash point of about 145° F, it has a very high hot surface ignition temperature -which is mandatory for weeping tanks. DFM and JP would not tolerate an environment over 400- 425° F.]

Gas path deposition - Regarding the effects of deposits in the gas path, (see the Propulsion Appendix) large 100,000 HP, land based turboshaft engines used for power generation (GE Frame 7 and WE501) have made an operational allowance for the fact that air entrained dirt at ground level will adhere to the gas path, even with filtration, and this can be substantial. Operators are instructed to watch for rises in compressor pressure ratio and EGT typical of gradual buildups of water soluble salts on the first stage

turbine vane flow area. Rises of 100° F are not untypical. The "fix" is to motor the engine over with a 1500 HP diesel at low RPM and cool it off, then inject the compressor with fresh water, soap (B&B) and then rinse with fresh water. Virtually total performance restoration is the rule. If the restoration is not within 1% of new, a slightly abrasive ground walnut shell (carbo-blast) is injected with the engine running at idle.

Development Consortia - NASA and ARPA are the only two Agencies in the federal government today who can make and fund agreements for development (and improvement of production products) where govt. procurement is not involved. NASA can do so under the Space Act Agreement of 1958 and the activity in its totality is neither competitive nor does it fall under agency procurement or the procurement regulations. Work done also escapes FOIA for up to five years. It requires the approval of NASA General Counsel and the administrator. General Counsel is not adverse to funded agreements under the 1958 Space Act, but has difficulty in being perceived as going around procurement in order to make the needed technical activity happen smoothly with a minimum of federal involvement. The number of funded Space Act agreements that have actually been consummated is believed to be two or three as of 1 May 1994. ARPA is believed to have a very similar capability under 103-160 sec 845 but some competition is required initially in establishing who falls under the program. ARPA's effort is also not a procurement and results in an agreement, not a contract. Interestingly, ARPA's use of 103-160 sec 845 is appropriate when normal use of the regs, milspecs and directives need not necessarily apply. Using commercial development practices would be such a situation.

Reference

1. "Marks' Standard Handbook for Mechanical Engineers", 8th Edition. Chapter 11 -41. Horspower per Ton Versus Froude Number. McGraw Hill.

Appendix C - Structures

LOCKHEED-GEORGIA WINGSHIP

Principal characteristics of the Lockheed design (Reference 1) are as follows:

Logistics Mission		
Payload	441,000 Lb	(200,038 Kg)
Range (Seastate 3)	4000 N. Mi.	(7408 Km)
Range (Seastate 4)	3722 N. Mi.	(6893 Km)
Cruise Speed	0.40 Mach	
Cruise Altitude (Sea State 3)	3.81 Ft	(1.16 M)
Cruise Altitude (Sea State 4)	5.26 Ft	(1.60 M)
Maximum Sea State Capability	4	

Dimensions		
Length 238.5 Ft	(72. 7 M)	
Height 34 Ft	(10.36 M)	
Wing Span	108 Ft	(32.92 M)
Wing Chord	91 Ft	(27.7 M)
Wing Area	9,828 Ft^2	(913.1 M^2)
Wing Thickness Ratio	0.25	
Wing Loading	138.15 lb/Ft^2	(674.5 Kg/M^2)
Wing Aspect Ratio	1.19	
Wing End Plate Height	9.1 Ft	(2.8 M)
Cargo Compartment Width	50.25 Ft	(15.3 M)
Cargo Compartment Maximum Height	13.5 Ft	(4.1 M)
Cargo Compartment Length	108 Ft	(32.92 M)

Propulsion Engines	
Number	Four (4)
Type	BPR 30 Turbofan
Rating (SL Static, Uninstalled)	95,600 lb (425,230 Newtons)

<u>Hydrofoil:</u>
Planform area = 115 ft^2 (10. 7m2), L/D = 3, hydraulic actuation with failure mode in the extended position. Maximum load at impact speed of 150 fps (46 mps) is 776,250 lb (11,252kN).

<u>Wing Flaps:</u>
Used as hydrodynamic drag plate in landing mode. 40 degree (0.70 rad) deflection with load relief incorporated at a load exceeding 3,840 lb/ft^2 (18,749 kg/m^2). 20° deflection for takeoff.

<u>Wing End Plates:</u>
Height = 9.1 ft (2. 8 m)
Height to chord ratio = 0.1
Max. width = 2 ft (0.61m)
Leading edge half angle = 45 (0.79 rad)
Leading edge cant angle = 30° (0.52 rad)
Lower surface included angle = 24 (0.42 rad)

Maximum side load = 1.76 x 106 lb (7828 kN)

Flight Controls
4 channel electrical fly-by-wire system with a hydro-mechanical backup channel.

Hydraulic System
Four 5000 psi (34,473 Pa) systems, inflight power source - engine driven pumps, ground power source - electrically driven pumps.

Weights	lb	kg
	357,900	162,343
Empty Weight (Fraction = 26%)	441,000	200,038
Payload	221,379	100,398
Structural Weight (Fraction = 16%)	798,900	362,381
Zero Fuel Weight	563,100	255,422
Maximum Fuel	1,362,000	617,803
Maximum Full Load Weight		

Performance Summary		
	0.4 Mach/Sea Level	
Maximum Speed/Altitude	0.4 to 0.26 Mach/Sea Level	
Best Range Speed/Altitude	24,795 ft	(7,557.5 m)
Acceleration Run	12,117 ft	(3,693 m)
Deceleration Run	4000 n. mi.	(7,408 km)
Maximum Range at Full Payload	5,180 n. mi.	(9,593 km)
Maximum Range at Zero Payload (0.4 Mach)	5,630 n. mi.	(10,427 km)
Maximum Range at Zero Payload (LRC)	15.6	
Initial Cruise L/D	15.39 hrs.	
Design Mission Duration	5.70	
Effective Aspect Ratio		

NORTHROP 1.6M WINGSHIP

Physical characteristics of the Northrop wingship are summarized as follows:

Dimensions	
Length 282 ft	
Height 70 ft	141.4 ft
Wing Span	65 ft
Wing Root Chord	44.7 ft
Wing Tip Chord	7,778 ft^2
Wing Area	approx 8 %
Wing Thickness Ratio	206 lb/ft^2
Wing Loading	2.6
Aspect Ratio	

Propulsion Engines (flight)
(4) Fixed pitch Advanced Technology bypass ratio turbofans, about 84,000 lb SLS thrust each.

NORTHROP WINGSHIP 1.6M WEIGHT BREAKDOWN

(All weight values in pounds)

ITEM	WEIGHT

Structure	(527,836)
Wing	159,052
Horizontal	48,742
Vert Tail	33,700
Fuselage	180,143
Landing Gear	46,173
Engine Sect	60,026
Propulsion	(158,233)
Engines	68,702
Other Propulsion Items	89,531
Including: AMAD	
Controls	
Starting	
Fuel System	
Systems and Equipment	(65,300)
Flight Controls	12,446
Auxiliary Power	1,368
Instruments	759
Hydraulics	11,349
Electrical	6,253
Avionics	4,000
Furnishings and Equip	21,361
ECS and Anti-icing	7,124
Load and Handling	640
WEIGHT EMPTY	751,369
Operational Items	11,199
Crew	
Engine Oil	
Unusable Fuel	
Miscellaneous	
OPERATING WEIGHT	762,568
Payload	320,000
Fuel Usable	517,432
BASIC MISSION TOGW	1,600,000

Note that these values indicate a structural weight fraction of 32%, and an empty weight fraction of 47%.

DOUGLAS AIRCRAFT WINGSHIP (Wingship-S)

Principal characteristics of the Douglas Wingship-S (Reference 2) are as follows:

Dimensions	English	Metric
Length	261.25 ft	79.63 m
Height	56.50 ft	17.22 m
Wing Span	108.00 ft	32.92 m
Wing Chord	92.6 ft	28.2 m
Wing Area	10,000 ft^2	929m^2
Wing Thickness Ratio	15%	15 %
Wing Loading	200 lb/ft^2	977kg/m^2
Aspect Ratio	1.166	1.166

Power Plants

Propulsion Engines (flight)

(6) Fixed pitch Advanced Technology bypass ratio 12 turbofans, 95,000 SLS thrust each. No thrust reversers.

Propulsion Engine (sea maneuvering)

(1) 30 inch retractable screw hydraulically driven.

Fuel: 1,317,048 pounds usable fuel or 202,623 gallons in six tanks; two self-sealing.

Electrical: Four 180 KVA channels, APU powered.

Hydraulic: Two 4000 psi systems of 50 gpm capacity, APU powered.

Control: Power-by-wire servo pump actuator primary flight controls.

	Metric	English
Weights	907,200 kg	2,000,000 lb
Maximum Full Load Weight	113061 kg	249,300 lb
Structural Weight (Fraction = 12.5%)	229,937 kg	506,916 lb
Empty Weight (Fraction = 25%)	597,409 kg	1,317,048 lb
Maximum Fuel (usable)	46,095 kg	101,620 lb
Maximum Payload	333,004 kg	34,136 lb
Landing Weight		

AEROCON DASH-1.6

The AEROCON DASH 1.6 wingship design has the following physical characteristics:

FUSELAGE	566 ft
Length (overall)	112 ft
Maximum Height	86 ft
Max Beam (w/o Strake)	116 ft
Max Beam (W/Strake)	

WING	
Span 340.00 ft	156.00 ft
Root Chord	60.00 ft
Tip Chord	4.69 ft
Tip Thickness	38,720.0 ft^2
Wing Planform Area	3.15
Aspect Ratio	0.38
Taper Ratio	23.15 degrees
L.E. Sweep	16.95
Quarter Chord Sweep	-9.00
T.E. Sweep	

PROPULSION BRIDGE	236 ft
Overall Span	64 ft
Root Chord	13,087 ft^2
Gross Area	4.25
Aspect Ratio	.47
Tip Chord	0.73
Taper Ratio	19.60
Leading Edge Sweep	17.78
Quarter Chord Sweep	

EMPENNAGE

Overall Span	320.00 ft
Root Chord	85.00 ft
Root Thickness	8.66
Tip Chord	33.00
Tip Thickness	3.50 %
Empennage Planform-Span Area	18,680.0
Planform-Span Aspect Ratio	5.42
Taper Ratio	0.39
Flight Control Surface Area	2,632.0

The AEROCON DASH-1.6 wingship Design has the following performance parameters:

Takeoff Gross Weight, WO	5,000 tons
Empty Weight, WE = .3588 WO	1,794 tons
Max Fuel, WF max = .52 WO	2,600 tons
Max Payload, WP max = .345 WO	1,725 tons
Max Payload at WF max	606 tons
Wing Loading	258 lb/ft^2
Takeoff Speed (Based on $C_L = 1.0$)	276 knots
Cruise Velocity, VC	400 knots
Cruise (clearance) Altitude, HC	12 feet
Cruise L/D	32.5
Cruise thrust specific fuel consumption	0.55
Reserve alternate field distance	350 nmi
Additional reserve allowance	5%

(Fuel for an additional 5% of the total flight distance including alternate destinations)

WEIGHT BREAKDOWN of AEROCON DASH 1.6. (Note all weight values are in lb.)

STRUCTURES GROUP

Wing Structure Weight	616,926
Empennage Structure Weight	360,870
Surface Controls Weight	57,690
Fuselage Structure Weight	821,976
Propulsion Bridge Weight	217,475
Total Structure Weight	2,074,937
Structural Weight Fraction	20.7%

PROPULSION GROUP

Unit Engine Weight	12,819
Number of Engines	16
Total Uninstalled Weight	205,104
Total Installed Weight	262,533

FIXED SERVICES AND EQUIPMENT GROUP

Electrical	56,380
Hydraulics & Pneumatics	60,600
Conditioning Systems	20,700
Equipment & Actuators	137,680
Sensors	14,500

	7,950
Mission Systems	388,275
Furnishings	88,760
Emergency	1,037,695
Total Fixed Services & Equipments	3,375,165
Basic Empty Weight	33.7%
Empty Weight Fraction	213,600
Operational Item Weights	3,588,765
Operational Empty Weight	

MISSION USEFUL LOADS (Max Payload)	
Crew 4,500	
Troops 875,000	
Cargo 2,570,000	3,445,000
Total Payload	34%
Payload Weight Fraction	3,449,500
Total Mission Dry Load	34%
Mission Dry Load Weight Fraction	2,897,500
Fuel Useable	152,500
Reserve Fuel	3,050,000
Mission Fuel	2,400
Oil and Hydraulic Reserves	3,052,400
Total Mission Fuel & Lubricants	10,090,665
Mission Take-off Gross Weight	

DASH-1.6 GROSS WEIGHT LIMITS	10,692,000
Max Takeoff (Water w/PAR)	8,200,000
Max Takeoff (Water w/o PAR)	4,700,000
Max Takeoff (Land w/PAR)	10,000,000
Max Water Landing	6,700,000
Max Land Landing	

CONSTRUCTION MATERIALS

The following are excerpts from Reference 3 on the assessment of construction materials based on large Soviet wingship experience. This should provide a point of departure for material considerations of any large wingships that the U.S. may anticipate building in the future.

Construction materials exert a substantial influence on the tactical-technical and economic characteristics of wingships. Requirements for materials are stringent by virtue of the high stresses impossed on the structures, which are operated in an aggressive sea environment, and also in a complex combination of hydro-aerodynamic, vibration, acoustic forces.

In the construction of wingships, aluminum and titanium alloys, highly durable and non-rusting steels, plastic and other composite structures can be used. The characteristics of a number of materials are cited in Table I.

A large part of the structures of the hull, wings and stabilizer are made from an aluminum-magnesium alloy AlMg 61, which possesses comparatively low values of yield and tensile limits, but which has good plasticity, ability to be welded and corrosion resistance.

For the purpose of further structural optimization and improved weight efficiency, it is necessary to apply more high-durable welded aluminum alloys (with a yield limit near 30 kgs/mm^2 and a tensile limit more than 40 kgs/mm^2).

High-durable aluminum alloys of the system "aluminum-zinc-magnesium" type "K48-2PCHT1" are used for decks, partitions and thin-walled structures where riveting is required.

TABLE C-1

Characteristics		Aluminum Alloy					Steel			Composites		
		AMg 61	1985 chi	D16 AT	K48-2 pch		12X18 H10T	30XGCA	BHC 2	BKA-16	KMY-3c	KAC 1A
Mechanical Qualities	σ_b, kg/mm^2	34	42	43.5	44		54	110	105	90	70	130
	$\sigma_{0.2}$, kgs/mm^2	18	26	28	35		24	85	95	-	-	-
	σ, %	15	13	11	9		38	10	10	-	-	-
	E$\cdot 10^6$ (kg/cm^2)	0.7	0.7	0.7	0.72		2.0	2.1	1.9	2.0	1.4	1.17
Endurance limits for bending model with symmetrical cycle at base $2 \cdot 10^7$ cycles	Cut model σ_{-1}^{H} (kg/mm^2)	5	6.5	8	10		•	22	47	•	•	35
	Smooth model σ_{-1} (kg/mm^2)	12	13	14	15		21	48	55	•	•	•
	Welded join σ_{w} (kg/mm^2)	6	7	-	-		9.5	-	34	2.7	1.5	4.5
Specific Density, γ g/cm^3		2.64	2.69	2.8	2.77		7.9	7.9	7.76	•	•	•
Plastic Reserve $\sigma_{bp}/\sigma_{0.2}$		1.9	1.6	1.5	1.3		2.2	1.4	1.1	•	•	•
Specific Stability-hardness coefficient $\sqrt{E(0.65\sigma_{bp}+0.35\sigma_{0.2})}\cdot\dot{\gamma}\cdot 10^4$ km		1.54	1.75	1.74	1.9		1.05	1.91	1.76	•	•	•
Criterion for endurance $\sigma_{-1}/\sigma_{0.2}$		0.67	0.5	0.52	0.43		0.88	0.62	0.58	•	•	•
Critical coefficient, Intensity of tension K_{lc} kg/m$^{3/2}$		130	125	110	100		450	-	400	•	•	•

Alloys of the "aluminum-copper" system of D16 type have been successfully used in aircraft structures. They have acceptable tensile characteristics, they can be readily handled in production and repair, but they are noted for lowered corrosion resistance and also for a tendency for intercrystal corrosion. It is not desirable to apply them in remote and humid areas. However, one must note that the application of the alloy D16AT on two wingships (a 500-ton boat model and a self-propelled SM-6 model with a take-off weight of 25 tons) showed that this alloy could ensure a "fairly lengthy period of operation".

Non-rusting steels of the 12X18NIOT type are mostly used for pylon structures. Increased requirements in fire-resistance and safety during the application of large dynamic stress are made on these structures. High-durable steels of the 30XGSA type are used for support of engines, hydrodrives and other units.

"The weight efficiency of the structures, using composite materials, can be increased by 30% and more." One of the promising applications of high-durable composite structures is reinforcing elements in junctions of linkage of traditional primary structures with the aim of ensuring equal durability for the entire section. Experimental research of the wingship wing has confirmed the effectiveness of such reinforcement. It should be noted that the price of composites is high thus far, and in production they are noted for their more complicated and delicate technology; therefore, the advisability of their application in each specific situation should be evaluated not only from technological, but also from the aspect of economics. Foreign experience shows that a

significant reduction in the cost of structures made from composites can be achieved through their mass production in specialized and well-automated productions, e.g. during mass production.

Positive qualities received from the application of composite materials in wingship structures allow us to consider them one of the most promising directions of the optimization of wingship hull structures.

The structure of a wingship has classic aircraft elements, but on the other hand has certain distinguishing features requiring a number of fundamentally new solutions. This relates most of all to the method of joining the structures. Self propelled wingship models of the 1960s were mostly riveted. For the creation of the 500-ton KM wingship and the transport-landing "Orlenok" ["Eaglet"] wingship, more than 60% of the structures were fully-welded. On the "Loon" ["Harrier"] wingship, more than 90% of the structures were fully-welded (only the thin-walled structures of the deck, the auxiliary partitions, and the ends of the stabilizer were made with rivets).

By itself, this solution is unique, since, for the first time in the history of flying apparatus, a fully-welded wingship structure was created. This became possible due to the use of the weldable, corrosion-resistant and plastic alloy AMg-61, which is capable, under high levels of stress, of safely redistributing loads to less stressed structures. It should be noted that the use of welded structures of light alloys required conducting an exceptionally large series of experimental tests.

Another distinctive feature of wingship structures is the use of multi-sparred designs. A multi-sparred structure possesses an advantage in that its failure under limited stress does not usually lead to catastrophic consequences for the wingship.

A classic design of joining the hull with the wing, used on the "LUN" wingship is the use of the cross structure built into the hull. The figure below shows the approaches for "LUN", ORLAN and the KM.

The cross structure and the cantilever part of the wing of the wingship do not have an "operative separation on board", as they do on an airplane. For the purpose of ensuring the necessary malleability and removal of the concentration of stress, joining the cross structure with the hull is usually done by high-durable bolts. Among the most important distinguishing features of wingship structures that should be noted is the wide use of monolithic, fully-pressed panels (volume of use on one of the wingship projects reached 80% of the general surface of the apparatus).

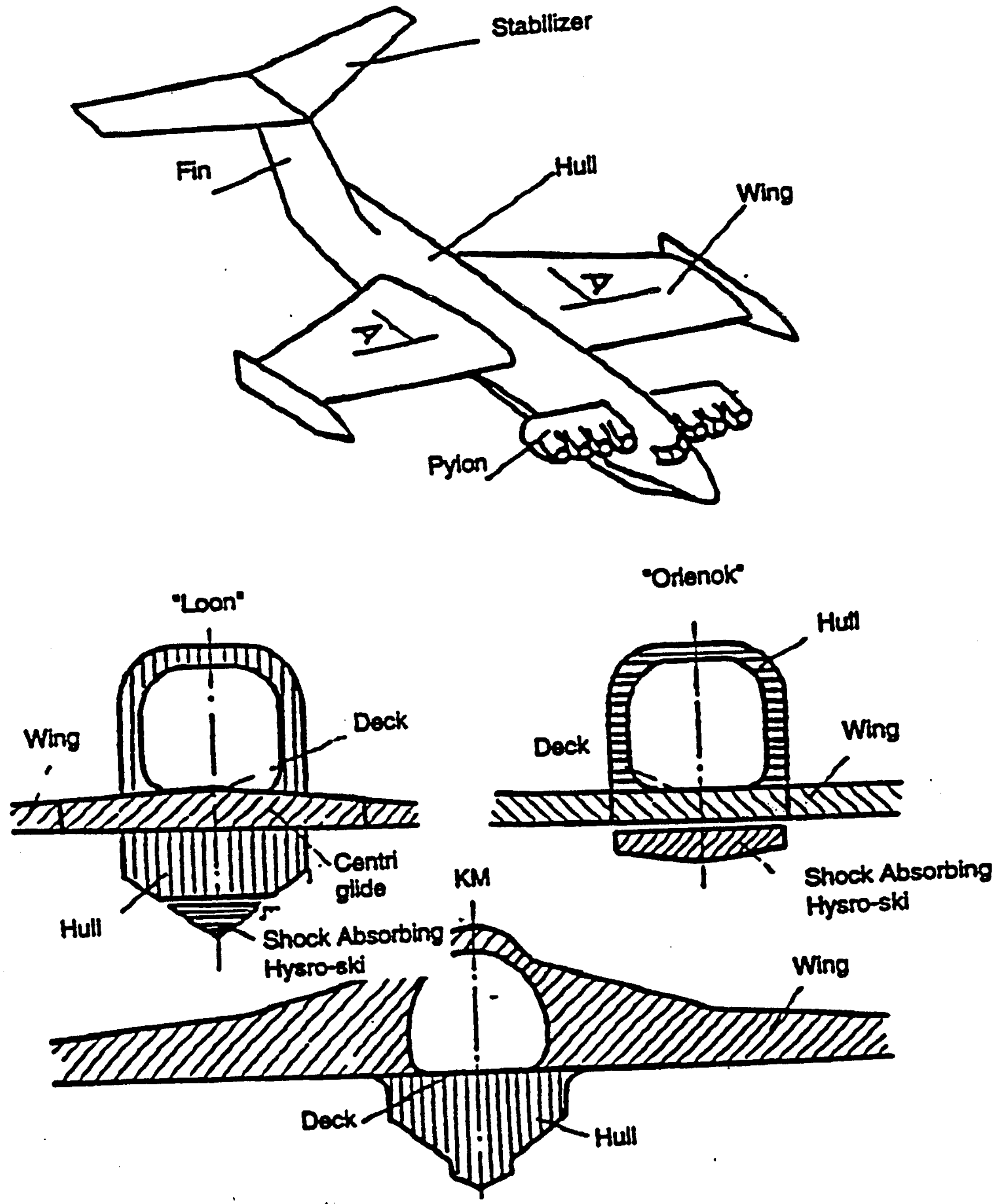


Figure C-1 - Classic Design of Joining the Hull with Wingship Wing2

Appendix C- Sructures References

1. "Parametric and Conceptual Design Study of Aircraft Wing-in-Ground Effect (WIG) Vehicles", Lockheed Georgia Co. Report Number 76020-30, May 1977. (ANVCE)

2. "Point Design for WIG-S", Volume IV - Structural Analysis, Douglas Aircraft Report MDC J7406-4, March 1977. (ANVCE)

3. "Wingship Compendium", A Review of Russian Design/Engineering on Wing-In- Ground (wingship) Effect Vehicles, by A. Maskalik and V. Treschevsky (translated by G. Libman and V. Mishkevich), Office of Naval Research Science Opportunities Program, 1992.

Appendix D - Actuators

LARGE WINGSHIP FLAP LOADS ESTIMATION

The following is a rough calculation of wing flap loads and actuator requirements for a series of Wingship sizes.

LOAD ESTIMATION ON FLAP OF WING WITH A 20% CHORD FLAP

Flap load from Reference 1 with assumed d = 30– flap deflection, and wing angle of attack, a = 1– , gives q = 1/2_V^2 = about 1.0

Example: ORLAN

Gross weight = 250,000 lb. = 125 Tons
Wing span = 103.4 ft
Wing chord = 31.2 ft
Wing area = 3,226 ft^2
Wing loading = 77.5 lb/ft^2
Flap chord = 0.20 x 31.2 = 6.24 ft
Flap span (assuming 6 sections) = 103.4/6 = 17.3 ft
Flap area = 17.3x6.24 = 108 ft^2
If takeoff speed is 140 knots = 236 ft/sec,
Aero load on flap = 1/2 x .002378 x 108 x 236^2 = 7,139 lb
Moment about flap L.E. = 1/4 x 6.24 x 7,139 = 11,137 ft-lb

If actuator acts at flap hinge point offset of about 8in.=.66 ft ;

then actuator load = 11,137/.66 = 16,874 lb.

Example: LUN

Gross weight = 800,000 lb = 400 Tons
Wing span = 144 ft
Wing chord = 43.6 ft
Wing area = 6,278 ft^2
Wing loading = 127 lb/ft^2
Flap chord = 0.20 x 43.6 = 8.72 ft
Flap span (assuming 6 sections) = 144/6 = 24 ft
Flap area = 8.72 x 24 = 209 ft^2
According to Reference 2, p 35,
Takeoff speed is 340 km/hr = 183 knots = 309 ft/sec
Aero load on flap = 1/2 x .002378 x 209 x 309^2 = 23,689 lb
Moment about leading edge (L.E.) = 1/4 x8.72 x 23,689 = 51,642 ft-lb

If actuator acts at flap hinge point offset of about 1 ft ;

then actuator load = 51,642 lb

LUN Wingship flap actuator reported in reference 1 has a maximum output force of 42,716 lb. The calculated value of 51,642 is conservative and is for one actuator per flap section. Therefore, propose to use this approach to estimate actuator load requirements for larger Wingships.

If we further assume that the 30° flap deflection is to be accomplished in 3 seconds; the actuator horsepower is:

51,642x.66xTan30°/(550x3) = 11.8 hp.

Lockheed Georgia Wingship Flap Load Calculation

Gross weight = 1,362,000 lb = 681 Tons
Wing span = 108 ft
Wing chord = 91 ft
Wing area = 9,828 ft^2
Wing loading = 139 lb/ft^2
Flap chord = 0.20 x 91 = 18.2 ft
Flap span (assuming 6 sections) = 108/6 = 18 ft
Flap area = 18.2x18 = 328 ft^2
Takeoff speed = $(L/1/2x.002378xAxC_{Lmax})^{1/2}$
With C_{Lmax} = 1.0;
Takeoff speed = $(1{,}362{,}000/1/2x.002378x9{,}828x1.0)^{1/2}$ =341 ft/sec=202 kts
Aero load = 1/2 x .002378 x 328 x 341^2=45,349 lb
Moment about flap L.E. = 1/4 x 18.2 x 45,349=206,338 ft-lb

We assume for, these larger systems, that each actuator package contains two actuator working in parallel and there are two packages driving each flap section. These packages will of course have to be synchronized so as to not to introduce a twist in the flap structure. We also assume that the actuator packages act at flap hinge point offset of about 1 ft.

Then each actuator load = 51,585 lb.

If we further assume that the 30° flap deflection is to be accomplished in 3 seconds; the actuator horsepower is: 51,585x1xTan30°/(550x3)=18 Hp.

This appears to be within the current state-of-the-art.

Northrop M1.6 Wingship Flap Load Calculation

Gross weight = 1,600,000 lb = 800 Tons
Wing Span = 141.4 ft
Wing Chord (Average) = 55 ft
Wing area = 7,778 ft^2
Wing loading = 206 lb/ft^2
Aspect Ratio = 2.6
Flap chord = 0.20 x 55 = 11 ft
Flap span (assuming 6 sections) = 141.4/6 = 23.6 ft
Flap area = 18x23.6 = 259 ft^2
Takeoff speed = $(L/1/2x.002378xAxC_{Lmax})^{1/2}$
With C_{Lmax} = 1.0;
Takeoff speed = $(1{,}600{,}000/1/2x.002378x7{,}778x1.0)^{1/2}$ = 415 ft/sec=246 kts

Flap aero load = $1/2 \times .002378 \times 259 \times 415^2 = 53{,}037$ lb
Moment about flap L.E. = $1/4 \times 11 \times 53{,}037 = 145{,}852$ ft-lb

Again we assume for, these larger systems, that each actuator package contains two actuator working in parallel and there are two packages driving each flap section. These packages will of course have to be synchronized so as to not to introduce a twist in the flap structure.

We also assume that the actuator packages act at flap hinge point offset of about 1 ft.

Then each actuator load = 36,463 lb.

If we further assume that the 30° flap deflection is to be accomplished in 3 seconds; the actuator horsepower is:

$36{,}463 \times 1 \times \text{Tan}30^{\circ}/(550 \times 3) = 13$ Hp.

This appears to be within the state-of-the-art.

Douglas Aircraft Wingship Flap Load Calculation

Gross weight = 2,000,000 lb = 1,000 Tons
Wing Span = 108 ft
Wing Chord = 92.6 ft
Wing area = 10,000 ft^2
Wing loading = 200 lb/ft^2
Flap chord = 0.20 x 92.6 = 18.5 ft
Flap span (assuming 6 sections) = 108/6 = 18 ft
Flap area = 18.5x18 = 333 ft^2
Takeoff speed = $(L/1/2 \times .002378 \times A \times C_{Lmax})^{1/2}$
With $C_{Lmax} = 1.0$;
Takeoff speed = $(2{,}000{,}000/1/2 \times .002378 \times 10{,}000 \times 1.0)^{1/2} = 410$ ft/sec=242 kts
Flap aero load = $1/2 \times .002378 \times 333 \times 410^2 = 66{,}557$ lb
Moment about flap L.E. = $1/4 \times 18.5 \times 66{,}557 = 307{,}826$ ft-lb

Again we assume for, these larger systems, that each actuator package contains two actuator working in parallel and there are two packages driving each flap section. These packages will of course have to be synchronized so as to not to introduce a twist in the flap structure.

We also assume that the actuator packages act at flap hinge point offset of about 1 ft.

Then each actuator load = 76,957 lb.

If we further assume that the 30° flap deflection is to be accomplished in 3 seconds; the actuator horsepower is:

$76{,}957 \times 1 \times \text{Tan}30^{\circ}/(550 \times 3) = 26$ Hp.

CONCEPTUAL 2,300 TON Wingship Flap Load Calculation

Flap load and actuator load requirements here are based on wing loading trends, taken as 225 lb/ft^2 and an aspect ratio of 2.

Gross weight = 4,600,000 lb = 2,300 Tons
Wing span = 202 ft
Wing chord = 101 ft
Wing area = 20,444 ft^2
Wing loading = 225 lb/ft^2
Flap average chord = 0.20 x 101 = 20 ft
Flap span (assuming 8 sections) = 202/8 = 25.2 ft
Flap area = 20x25.2 = 504 ft^2
Takeoff speed = $(L/1/2x.002378xAxC_{Lmax})^{1/2}$
With C_{Lmax} = 1.0;
Takeoff speed = $(4{,}600{,}000/1/2x.002378x20{,}444x1.0)^{1/2}$ =435 ft/sec=257 kts
Flap aero load = 1/2 x .002378 x 504 x 435^2 = 113,395 lb
Moment about flap L.E. = 1/4 x 20 x 113,395 = 566,973 ft-lb

Again we assume for, these larger systems, that each actuator package contains two actuator working in parallel and there are two packages driving each flap section. These packages will of course have to be synchronized so as to not to introduce a twist in the flap structure.

We also assume that the actuator packages act at flap hinge point offset of about 1.5 ft.

Then actuator load = 94,496 lb.

If we further assume that the 30° flap deflection is to be accomplished in 3 seconds; the actuator horsepower is:

94,496x1.5xTan30°/(550x3) = 50 Hp.

AEROCON DASH 1.6 Wingship Flap Load Calculation

Gross weight = 10,000,000 lb = 5,000 Tons
Wing span = 340 ft
Wing root chord = 156 ft
Wing tip chord = 60 ft
Average chord = 108 ft
Wing area = 38,720 ft^2
Wing loading = 258 lb/ft^2
Flap average chord = 0.20 x 108 = 21.6 ft
Flap span (assuming 10 sections) = 340/10 = 34 ft
Flap area = 21.6x34 = 734.4 ft^2
Takeoff speed = $(L/1/2x.002378xAxC_{Lmax})^{1/2}$
With C_{Lmax} = 1.0;
Takeoff speed = $(10{,}000{,}000/1/2x.002378x38{,}720x1.0)^{1/2}$ =466 ft/sec=276 kts
Flap aero load = 1/2 x .002378 x 734.4 x 466^2 = 189,621 lb
Moment about flap L.E. = 1/4 x 21.6 x 189,621 = 1,023,953 ft-lb

Again, we assume for, these larger systems, that each actuator package contains two actuator working in parallel and there are two packages driving each flap section. These packages will of course have to be synchronized so as to not to introduce a twist in the flap structure.

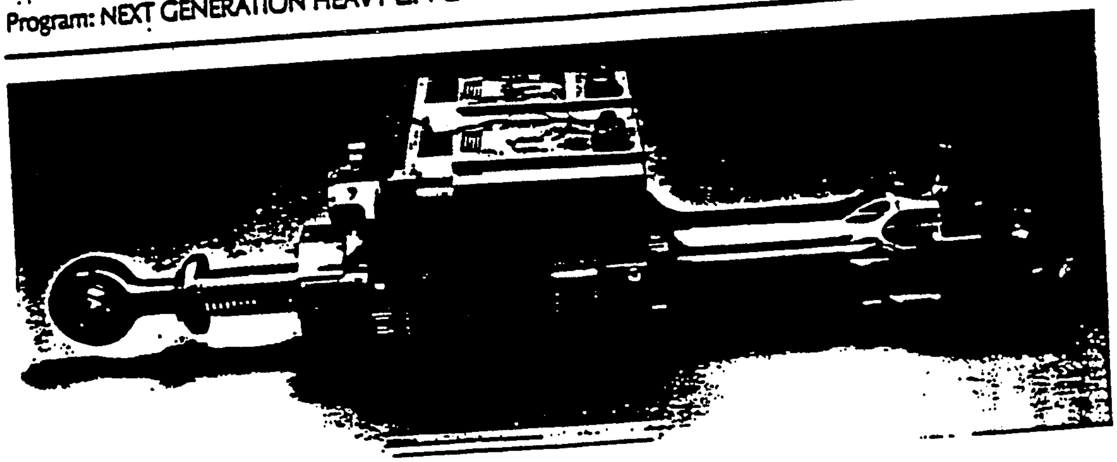
We also assume that the actuator packages act at flap hinge point offset of about 1.5 ft.

Then actuator load = 170,659 lb.

If we further assume that the 30° flap deflection is to be accomplished in 3 seconds; the actuator horsepower is: 170,659x1xTan30°/(550x3)=86 Hp.

THRUST VECTOR CONTROL (TVC) ACTUATOR

Type: Electromechanical, Dual Torque-Summed Motors
Program: NEXT GENERATION HEAVY LIFT LAUNCH VEHICLE



MOOG 38 hp Electromechanical Actuator

Performance Parameters

±5.5 in.
Output Travel .... 48,000 lbs
-Stall Force .... 100,000 lbs
Maximum Impulse Load ....
60 in/sec^2
Acceleration .... 38 hp
Rated Power .... 5.2 in/sec
Output Velocity .... 10 min
Duty Cycle .... 15,000 lbs
Average Load .... 270 vdc
Supply Voltage ....

MOOG
MISSILE SYSTEMS DIVISION

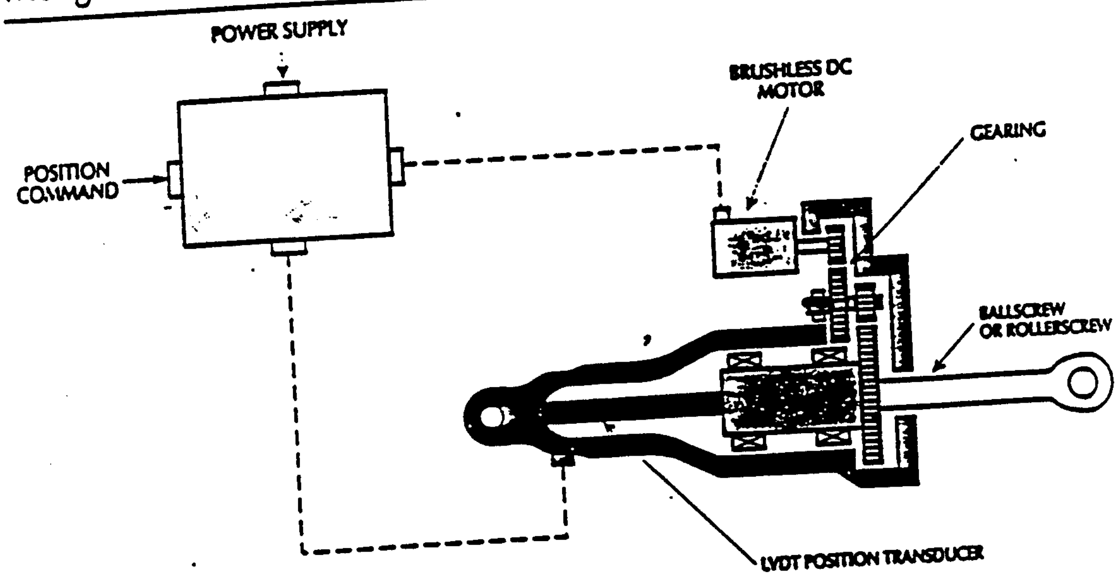
Form 500-47 682

THRUST VECTOR CONTROL (TVC) ACTUATOR

Features

- Custom permanent magnet brushless motor design.
  - Actuator design accommodates use of other motors such as induction or reluctance.
- Dual torque-summed motors for redundancy.
  - Each motor individually provides rated output force.
- Available with either a precision ballscrew or rollerscrew.
- Built-in LVDT for actuator output position signal.
- Overtravel stops to prevent damage in the event of a hardover failure.

Moog IR&D EMA TVC Actuation System



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NASA

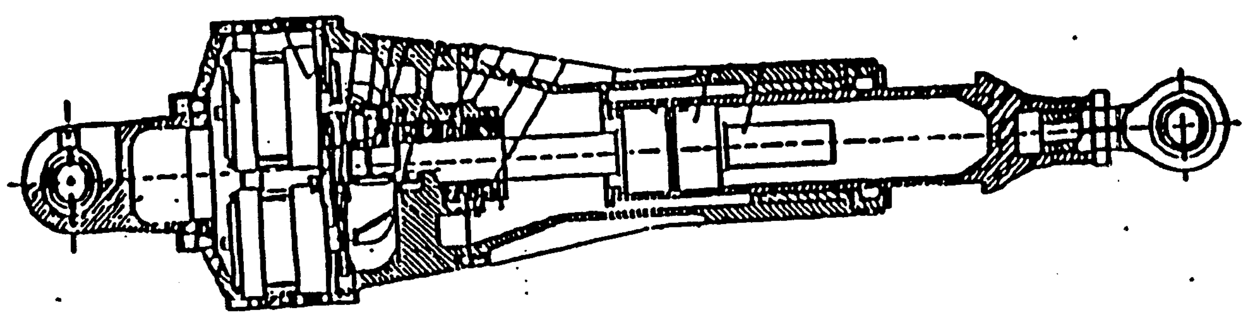
MSFC ADVANCED DEVELOPMENT PROGRAM

- THRUST VECTOR CONTROL SYSTEMS
  - DUAL CHANNEL 50 HP FEASIBILITY DEMONSTRATION UNIT
  - QUAD CHANNEL 60 HP SSME/SRB DEMONSTRATION UNIT
  - NLS TRIPLE- REDUNDANT DERIVED REQUIREMENTS AND SPECIFICATION

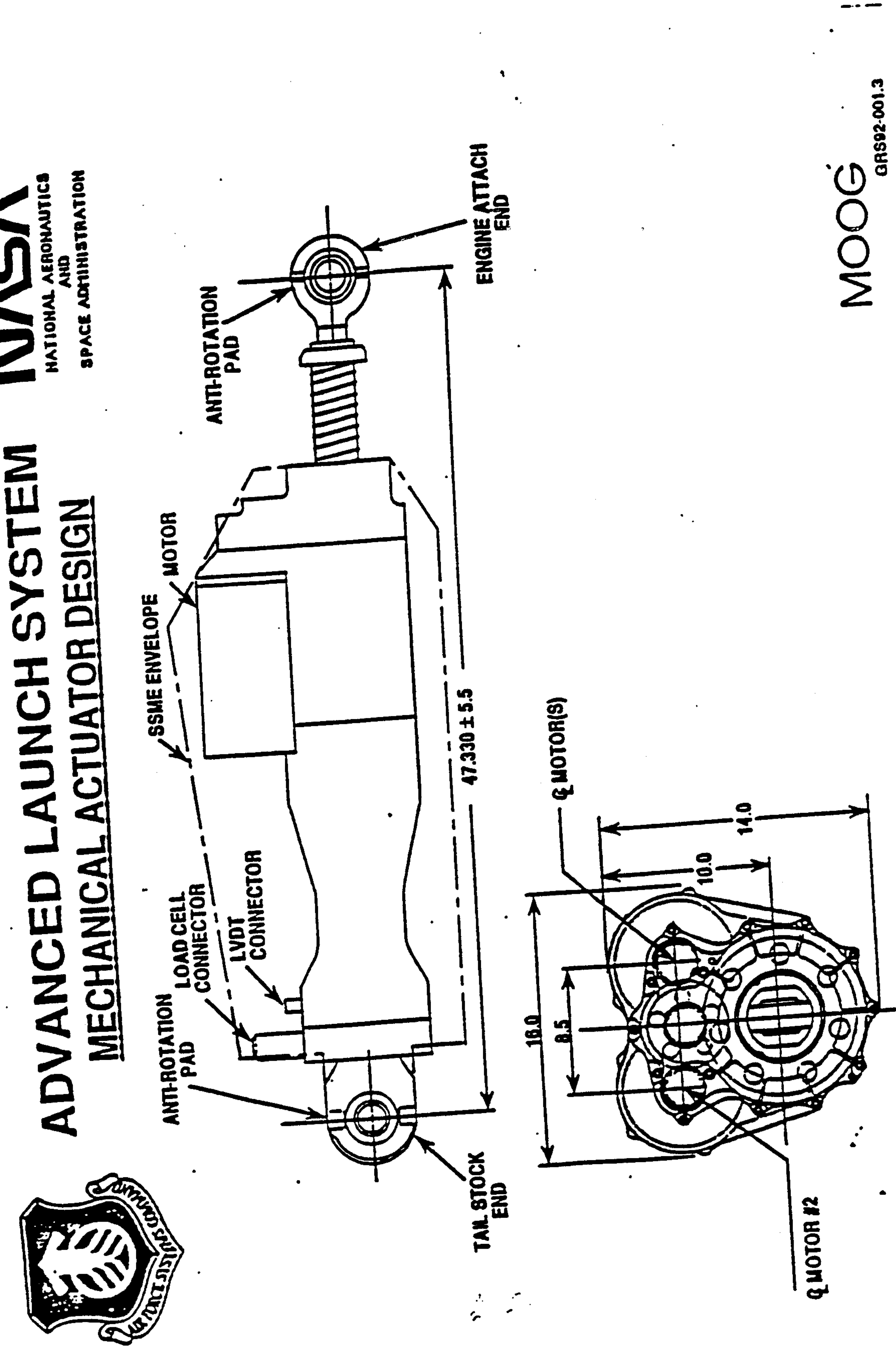
- ENGINE CONTROL VALVE SYSTEMS
  - MSFC SIMPLEX SSME MAIN OXIDIZER VALVE (MOV)
  - HR TEXTRON SSME MOV PROTO-FLIGHT UNITS
  - AEROJET STME PROPELLANT CONTROL VAVE UNITS

MSFC 50Hp EMA Actuator With Dual Permanent Magnetic Motors

- Rated Dynamic Capacity of 35,000 LB
- Maximum Stoke of +/- 5.25 in
- Rated Velocity of 5 in/sec
- Two 25Hp Permanent Magnet Brushless Motors
- 270V - 100A Power Source



MSFC - CONTROL MECHANISM & PROPELLANT DELIVERY BRANCH


ADVANCED LAUNCH SYSTEM
MECHANICAL ACTUATOR DESIGN
NASA
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
ANTI-ROTATION PAD
LOAD CELL CONNECTOR
LVDT CONNECTOR
SSME ENVELOPE
MOTOR
ANTI-ROTATION PAD
ENGINE ATTACH END
TAIL STOCK END
47.330 ± 5.5
℄ MOTOR(S)
14.0
10.0
16.0
8.5
VIEW A - A
℄ MOTOR #2
MOOG
GRS92-001.3

Aerospace Technology Directorate

NASA Lewis Research Center

FULL SCALE, 60 HP NLS DEMONSTRATION SYSTEM

- MOTOR CONTROLLER
  - DEDICATED DC-LINK, RESONANT POWER PROCESSOR
  - 60 kHz, 75 KVA
  - SHARED MICRO-COMPUTER CONTROL, FIBER-OPTIC INTERFACES TO PROCESSOR AND MOTOR
  - PRIMARY CONTROL ALGORITHMS CONTAINED IN SOFTWARE
- MOTOR
  - ADVANCED, LIGHTWEIGHT (<20 LBS) THREE-PHASE INDUCTION MOTOR
  - 30 Hp CONTINUOUS, 70 Hp PEAK AT 14,700 RPM
  - LOW LOSS, LOW INERTIA ROTOR
  - HIGH TEMPERATURE OPERATION TO 200 C
- LINER ACTUATOR
  - BALL SCREW WITH DUAL MOTOR DRIVE
  - 48,200 LB FORCE, 5.4 INCH EXTENSION
  - WEIGHT IS ABOUT 225 LBS

GRS92-005.13

References Appendix D - Actuators

1. Abbott, Ira H, and Albert E. Von Doenhoff, "Theory of Wing Sections", New York: Dover Publicatins, Inc. 1959, pg 194, Figure 99.

Appendix E - Results of Multi-Attribute Mission Ranking (20-24 June 1994)

Tabular Results of the Mult-Attribute mission ranking conducted at the Phase II Kickoff Meeting 20-24 Jun 94

Mission Attributes	ALTO	LIFT	ASWMV	AMCM	CECOC	TMD/ CRUISE	NTACMS	ALSOC	Drug Interdiction	Air Defense	Disaster Response	ALSS	Time-Critical Replenishment	CIP	ASW	Coast Guard SAR	Shallow Water ASW	HSAF	Commercial Transport
Need	825	1075	1000	1025	100	875	950	750	575	825	600	775	750	525	825	425	750	125	150
Importance	1025	975	1125	975	925	1275	900	860	600	850	475	625	475	350	800	275	775	200	275
Frequency of Occurrence	290	320	320	290	290	260	260	420	470	260	350	260	380	470	260	470	350	440	290
Technology Advancement Required	450	450	325	275	250	125	250	425	450	200	475	225	375	450	350	450	300	450	425
Sponsor	450	300	400	275	300	250	215	375	550	250	275	175	175	200	175	275	175	150	200
Acceptance	400	400	300	300	350	300	375	325	225	250	350	175	225	250	175	300	175	275	275
Funding Source	75	75	50	50	50	75	50	50	75	25	25	0	25	0	0	25	0	0	0
Potential Fleet Size	375	425	225	200	300	250	325	75	250	250	125	350	100	225	175	175	200	400	150
Multiple Use	225	325	275	275	275	225	200	175	275	225	300	275	300	275	175	275	125	125	250
Time Efficiency	700	700	650	700	650	700	700	660	625	625	750	550	550	600	375	650	500	750	675
Performance Effectiveness	600	550	550	575	550	560	550	625	625	400	500	500	525	525	475	450	350	675	525
Cost	125	25	25	100	75	125	125	75	75	100	50	0	25	0	25	0	25	25	25
TOTAL	5540	5520	5245	5040	5015	4940	4960	4695	4595	4360	4275	3910	3895	3870	3818	3770	3725	3615	3240
RANK BY SCORE	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
GROUP ASSIGNMENT	B	B	B	B	A	A	A	B	C	A	C	B	B	C	D	C	D	B	B

Appendix F - Rough Order Magnitude Cost Estimate of 400-Ton Wingship

ROUGH ORDER OF MAGNITUDE COST ESTIMATE OF 400-TON WINGSHIP

in support of

Contract No. MDA903-92-D-0056

U.S. Army Cost Economic Analysis Center (USACEAC)

Distribution limited to DOD and DOD Contractors only.

EXECUTIVE SUMMARY

In November of 1992 Congress directed the Department of Defense (DoD) to determine whether it had any interest in starting a wingship program. A wingship is a water-based aircraft that depends on the aerodynamic ground effect to enhance its flight performance. The craft must fly extremely close to the surface to benefit from the ground effect. The DoD's Advanced Research Projects Agency (ARPA) sponsored a two year study in response to the congressional direction. The study explores potential missions for wingships, examines Russian wingships, studies the application of existing and near term technologies to the Russian state of the art, and includes a future technology development roadmap for enhancements of wingship technology.

The roadmap recommends developing a first U.S. built wingship of 400 tons gross weight to begin a technology base for successively larger craft. This paper provides a rough order of magnitude (ROM) cost estimate of a 400 ton wingship and assesses the adequacy of current cost estimating methodology for this task.

The wingship is difficult to cost because of its many unique features, including its design for hydrodynamic loads, extreme size, operating environment, etc. Assumptions are shown below.

- Airframe is of all aluminum construction
- Gross weight is 800,000 pounds
- Weight empty is 400,000 pounds
- Maximum airspeed is 400 knots
- Total wetted area is approximately 28,670 square feet
- Design load is 6 g
- Engines are derivatives of large commercial turbofans
- Four (4) engines capable of 52-53,000 pounds of dry thrust each are required
- Avionics include navigation, flight control, and communication
- Avionics exclude military applications
- Navigation and flight control radar is adapted from existing millimeter wave radar at negligible cost
- Russian LUN is used as a test article during development

- The craft is built in the late 1990s
- One prototype is built and becomes operational.

This estimate includes ranges for the costs of development and first unit of the airframe, propulsion, and avionics.

WBS	Low	High
Airframe Development	$4,512 M	$4,901 M
Airframe First Unit	967 M	980 M
Propulsion Development	370 M	682 M
Propulsion First 6 Units	48 M	60 M
Avionics Development	89 M	172 M
Avionics for First Unit	59 M	59 M
Total Vehicle	$6,045 M	$6,854 M

A much higher estimate for airframe development and production was excluded because the estimator felt it was outside the reasonable range. The process of selecting appropriate estimating tools for the wingship program revealed the inadequacy of methods based on military aircraft experience. The problem is that many of the parameters of the wingship such as weight and the combination of design load and weight are outside the range of experience for the military aircraft upon which models are based. For example, the model that gave the excluded estimates is a log-linear form that is particularly sensitive to the input for ultimate design load. The wingship's design load of 6 g is higher than the normal load for a cargo aircraft, which is around 3.75. The model gave an airframe development cost of over $12 billion when the wingship's design load was input. In a sensitivity test at 4 g, the model gave the low estimate shown above. This illustrates the problem of extrapolating estimates beyond the range of existing data.

The wingship technology roadmap acknowledges the uncertainty of selecting materials and designing structures for a large wingship and suggests research in this area. Without either experience or more detailed theoretical knowledge of these problems, it is difficult to refine existing CERs based on conventional aircraft to estimate the cost of a wingship. Once studies are done on selecting materials and designing structures for wingships, or if a Russian wingship can be studied, then estimating CERs can be adjusted or an engineering estimate can be done to reflect the wingship's unique requirements.

TABLE OF CONTENTS

1. PURPOSE

In November of 1992 Congress directed the Department of Defense (DoD) to determine whether it had any interest in starting a wingship program. The DoD's Advanced Research Projects Agency (ARPA) sponsored a study in response to the congressional direction. The two year study explores potential missions for wingships, examines Russian wingships, studies the application of existing and near term western technologies to the Russian state-of-the-art, and includes a future technology development roadmap for further enhancements of wingship technology. The roadmap recommends developing an operational wingship of roughly 400 tons gross weight to begin a technology base for successively larger craft, provided that satisfactory solutions are found in several new technology developments. The purposes of this study are to provide a Rough Order of Magnitude (ROM) estimate of the cost of the first wingship and to discuss the adequacy of cost estimating methodologies for this unusual vehicle.

2. BACKGROUND AND SCOPE

A wingship is a water-based aircraft that depends on the aerodynamic ground effect to enhance its flight performance. The craft must fly extremely close to the surface to benefit from the ground effect. The Russians have built wingships of 150, 400, and 540 tons gross weight. The two smaller ships were concept demonstrators which have not become operational. The United States has not built any wingships although U.S. companies have produced designs for wingships of up to 1000 tons.

Potential missions for an operational wingship are being examined as part of ARPA's study. Potential missions include commercial, disaster relief, and military applications which take advantage of a large wingship's unique ability to carry large loads quickly over long distances and sit at sea.

The wingship technology development roadmap is based on the idea that four mission-oriented wingships, each of increasing size, will be developed and built. The most demanding heavy-lift long range missions require craft on the order of 5000 tons gross weight to achieve overall transport efficiencies which significantly exceed conventional aircraft. The largest wingship built for any operational concept demonstration is the Russian LUN at about 400 tons. The design of a structure significantly larger than this is seen as one of the most demanding obstacles to wingship technology development.

The sequence of building successively larger craft would build a technology base to ensure that a workable light weight structure can be built for the three largest craft. The first craft would be roughly the size of the Russian LUN, or roughly 400 tons gross weight. Each succeeding craft would be slightly more than twice as large as its predecessor. The first craft would be designed by 1996 and built by 2001. The following three craft would be built at ten year intervals. The program assumes that the LUN is purchased and used as a test bed concurrent with development of the first craft.

The roadmap includes sections on eight technologies--propulsion, structures, sensors and navigation, actuators, take off and landing technology, flight simulation, design methodology,

and flight testing. Three of the technologies—propulsion, structures, and take off and landing—are identified as risk areas and present unique design challenges not found in conventional aircraft. These risk areas correspond to the airframe and propulsion categories that account for the vast majority of costs in a cargo-type aircraft in a traditional work breakdown structure. The unique nature of the problems in these areas, the risk in solving the problems, the uncertainty about the nature of the design solution, and the fact that these areas compose the vast majority of the wingship's costs all add risk to the cost estimate.

Sections 4 through 8 address airframe, propulsion, and avionics costs according to the standard Work Breakdown Structure (WBS) category for an air vehicle. Each section presents an estimate and explains the methodologies used. The (WBS) for an air vehicle, the relevant section in this paper, and the methodology by which each area is addressed are summarized below.

WBS Category	Section	Method
Air vehicle	4, 5	two parametric models
Airframe	6, 7	expert judgment, parametric
Propulsion	8	analogy, parametric
Avionics		

The next section lists the ground rules and assumptions for the cost estimates.

3. GROUND RULES AND ASSUMPTIONS

- Costs are presented in FY95 dollars
- The airframe is built with all aluminum construction
- Gross weight is 800,000 pounds
- Weight empty is 400,000 pounds
- Maximum airspeed is 400 knots
- Total wetted area is approximately 28,670 square feet
- Design load is 6 g
- Engines are derivatives of large commercial turbofans
- Four (4) engines capable of 52-53,000 pounds of dry thrust each are required
- Avionics include navigation, flight control, and communication
- Avionics exclude military applications

- Navigation and flight control radar is adapted from existing millimeter wave radar at negligible cost
- Russian LUN is used as a test article during development
- The craft is built in the late 1990s
- One prototype is built and becomes operational.

4. AIRFRAME BACKGROUND, ESTIMATING METHODOLOGIES, AND DEVELOPMENT

Airframe cost refers to the cost of the basic structure, equipment homogeneous to the airframe, and the integration and installation of subsystems. This includes actuators which are the subject of one technology roadmap area.

Wingships present unique technology problems in structural design because they operate in air and water. Structures must be designed for both aerodynamic and hydrodynamic loads in highly corrosive conditions. In other words, the structure must be strong enough to hit the water but light enough and configured to fly efficiently. These factors create stringent requirements for design. An example of a design dilemma for a wingship structure is that the large structure size and load factor would suggest use of lighter composite materials, but some composite materials are poor energy absorbers and would not tolerate the water slamming loads absorbed by a wingship.

The technology roadmap spells out specific areas to be investigated to resolve structural issues, which become more difficult as the structure increases in size. Construction materials and water slamming loads are areas highlighted for study which particularly affect cost. It is more expensive to build with materials that are expensive and difficult to tool and shape. It is also more expensive to build a large structure to be very strong to absorb high loads.

Design uncertainty in these areas is mitigated in the case of the 400 ton wingship because the Russians have already built one of equal size. Based on Russian experience, it is assumed that the 400 ton wingship will be constructed of aluminum, designed to an ultimate load of 6 g, and have an empty weight of 400,000 pounds (200 tons).

Two parametric methods were used to estimate airframe costs. The first method is from a 1991 RAND study and was used to estimate non-recurring (development) and recurring (production) costs of the first unit. The second parametric method is from a model developed by Grumman for the Air Force and published in 1986. The Grumman model was used to estimate wingship airframe development and prototype costs.

4.1 *RAND Model Estimate of Airframe Non-Recurring Costs*

The RAND model is suitable for use in a program's conceptual stage when little detailed information is available. The method uses CERs to estimate several non-recurring and recurring

airframe cost elements such as recurring manufacturing labor, etc. The CERs were derived from a database of 13 military aircraft including the C-5, which has an empty weight almost as great as the wingship.

The airframe CERs from the RAND study based on a sample of 13 military aircraft are:

non-recurring engineering hours (000)	=	$.0168\ EW^{.747}\ SP^{.800}$
non-recurring tooling hours (000)	=	$.0186\ EW^{.810}\ SP^{.579}$
development support cost ($000)	=	$.0563\ EW^{.400}\ SP^{1.3}$
flight test cost ($000)	=	$1.54\ EW^{.325}\ SP^{.822}\ TESTAC^{1.21}$
recurring engineering hours (000)	=	$.000306\ EW^{.880}\ SP^{1.12}$
recurring tooling hours (000)	=	$.00787\ EW^{.820}\ SP^{.813}$
recurring manufact. labor hours (000)	=	$.141\ EW^{.820}\ SP^{.484}$
recurring manufact. material cost ($000)	=	$.540\ EW^{.921}\ SP^{.621}$
quality assurance hours (000)	=	.076 labor hours

EW = aircraft empty weight in pounds
SP = maximum speed
TESTAC = number of test aircraft

Man-hour values that result from these relationships are multiplied by fully burdened labor rates for different labor categories. The rates are given in FY90 dollars in the RAND study.

Engineering	$80.80
Tooling	$70.60
Manufacturing	$66.10
Quality Assurance	$65.60

Finally, adjustments are made for material complexity and the percentage of each functional cost element attributable to structure. These adjustments change the cost only slightly for an all-aluminum structure. The reader is referred to the RAND report for details. Dollar values were then inflated to FY95 dollars using DoD indices for RDT&E published in March 1994.

The basic inputs to the model are empty weight, maximum speed, number of flight test aircraft, type of aircraft (cargo or non-cargo), weight by material type, and percentage of functional cost elements attributable to structure.

Inputs for wingship were 400,000 pounds, 400 knots, 1 aircraft, cargo, all aluminum, and generic percentages of cost elements attributable to structure derived from the database, respectively. The selection of inputs for wingship was straightforward except for speed. The craft is expected to cruise at around 200 to 270 knots. However, it will have significant excess thrust at cruise because more thrust is needed for takeoff than is required for fuel-efficient flight at low altitude. A possible solution is to shut down some of its engines in the cruise mode as do the Russians. The principal author of the technology roadmap recommended use of a maximum speed of 400 knots.

The model estimates four non-recurring cost elements: non-recurring engineering encompasses the study, analysis, design, development, and evaluation of the basic airframe; non-recurring tooling includes the initial set of tools and all duplicate tools produced to permit a specific rate of production on a specific program; development support is the non-recurring manufacturing effort undertaken in support of engineering during the development phase of an aircraft program; flight test includes flight test costs incurred by the contractor.

The model estimated a total cost for non-recurring engineering, non-recurring tooling, and design support of $4,901 million.

4.2 *Grumman Model Estimate of Non-Recurring Costs*

The Grumman model is capable of predicting life cycle costs for military aircraft systems. It is based on data from a wide variety of aircraft of different types including fighter, attack, cargo, tanker, etc. The Grumman model requires more specific aircraft characteristics as inputs than does the RAND model. These inputs could be reasonably estimated for the design part of the Grumman model and it was used to provide an estimate of airframe design costs and prototype cost.

The Grumman model subdivided airframe development costs into five categories. The categories are total engineering labor, tooling labor, other direct charges which include special test equipment and tooling materials, first airframe manufacturing materials, and first airframe manufacturing and quality control labor. In this categorization, the first airframe is considered a prototype and therefore part of development. However, for the purposes of the wingship program, only one unit will be produced and it will be considered mission capable. The first three categories of airframe development costs are presented here as non-recurring, or design costs. The last two categories of costs to manufacture the first airframe are discussed in section 5.2. In that section the results of the Grumman model for the prototype aircraft are compared to the stepped up cost of the first production unit cost of the RAND model.

The airframe development CERs are shown below.

Total eng. labor (Mmanhours)	=	$(1.1609 \cdot 10^{7})\,(NZULT)^{2.5353}\,(TOGWCL)^{1.1933}$
Total tooling labor (Mmanhours)	=	$(7.6915 \cdot 10^{3})\,(PROTO)^{.53821}\,(TWTARA)^{.33606}$
Total other direct charges ($M)	=	$(3.5845 \cdot 10^{5})\,(NZULT)^{1.0906}\,(TGWMAX)^{1.4299}$

NZULT = ultimate load factor in g forces
TOGWCL = takeoff gross weight clean
PROTO = number of prototype and R&D aircraft
TWTARA = total wetted area (total external surface area of the aircraft excluding the canopy in square feet
TGWMAX = maximum takeoff gross weight

The most important inputs in this model are maximum gross takeoff weight and ultimate load factor. The input for maximum takeoff gross weight is given by definition in this case, because the wingship will be designed for a gross weight of 400 tons. The input for ultimate load factor was indicated by the June 19, 1994 draft of Volume I of the Wingship Investigation

Final Report. The report indicates that the Russian 400 ton wingship, the LUN, experiences hydrodynamic impact loads of 2.3 to 3.5 g. With a safety factor of 1.8, the design loads would be between 4.1 and 6.3 g. The model was run with an input of 6 g.

The model was also run with an ultimate design load of 4 g to show the sensitivity of the model to this input.

The takeoff gross weight clean is defined as maximum takeoff gross weight less external stores. No external stores are assumed for the wingship so these values are the same. Total wetted area was estimated at 28,670 based on areas provided by the principal author of the roadmap. The number of prototype aircraft is one.

The CERs for development costs result in values for millions of man-hours for engineering and tooling. These man-hour values were multiplied by the same labor rates as were used in the RAND study, and were then inflated to FY95 dollars using DoD indices for RDT&E published in March 1994. The results for development costs for the airframe were $12,675 million at an ultimate design load of 6 g and $4,512 million when the airframe is designed for an ultimate load of 4 g. Again, these figures do not include the costs of the first airframe.

5. AIRFRAME FIRST UNIT COSTS

5.1 *Estimated First Unit Airframe Costs in RAND Model*

The RAND model predicts the total cumulative recurring airframe costs for 100 airframes by functional cost element. The recurring cost elements are engineering, tooling, manufacturing labor, manufacturing material, and quality assurance. The model assumes a learning curve of a different rate for each cost element. Learning curve slopes for each cost element are shown below.

Cost Element	Cum Avg. Slope	Cum Total Slope
Recurring Engineering	70%	140%
Recurring Tooling	73%	146%
Manufacturing Labor	78%	156%
Manufacturing Material	87%	174%
Quality Assurance	78%	156%

To determine the cost of the first production wingship it is necessary to back up the learning curve from the predicted cumulative average cost of the 100th unit to the first unit cost for each cost element. This was done using the equation:

$$\text{First unit cost} = \text{cumulative total cost}_{100}/100^{\log \text{cumulative total slope \%}/\log 2}$$

The cost elements were totaled to a predicted first unit production cost of $744 million.

An additional adjustment is necessary to go from the first unit production cost to a prototype unit cost. Because only one 400 ton wingship will be designed and built and become operational, it is more accurate to cost it as a prototype rather than as a first production unit.

A study done by SAIC for the Strategic Defense Initiative Organization was used to go from the first unit production cost to prototype cost. The study examined the development to production step down effect and established factors for fighters, bombers, and cargo aircraft. The cargo aircraft had a development to production factor of .77. This means the first production unit was .77 lower than the last development unit cost. The reciprocal of .77, or 1.3, is used to step up from production to development and results in a prototype unit cost of $967 million.

5.2 *Estimated First Unit Airframe Costs in Grumman Model*

The Grumman model for development costs calculates the cost of manufacturing materials, labor, and quality control for the first airframe. The CERs are shown below.

First airframe manufacturing materials = $(8.4435*10^{-4})\ (NZULT)^{1.3787}\ (TGWMAX)^{.80442}$

First airframe manufacturing and quality control labor = $(5.0641*10^{-4})\ (NZULT)^{1.2478}\ (TGWMAX)^{.83651}$

The cost is $1,675 million in the 6 g case and $980 million in the 4 g case. The 4 g case is very close to the stepped up RAND estimate.

5.3 *Airframe Cost Estimate Summary*

In reviewing the estimates produced by the models, and comparing the estimates to costs for military cargo aircraft of similar size, it was decided to exclude the estimates given by the Grumman model with a design load of 6 g. Although the wingship's weight is only slightly outside the range of data, and the design load is within the range for all military aircraft including fighters, the combination of size and design load is outside the normal range for an aircraft. The model, which is a power function, is very sensitive to the combination and produces an unreasonable estimate.

	RAND Model	Grumman Model
Airframe Design	$4,901 M	$4,512 M low
Airframe First Unit	$967 M	$980 M low

6. PROPULSION BACKGROUND, ESTIMATING METHODOLOGIES, AND DEVELOPMENT

Wingships present a difficult problem in propulsion technology because they require much less engine thrust at their low operating altitude than they require for takeoff. The thrust to weight ratio at takeoff for wingships is roughly .25, the same as for large commercial aircraft. However, engines at sea level experience no loss in thrust due to altitude as do commercial aircraft flying at high altitudes. Therefore wingships suffer from considerable excess thrust at

cruise, which results in high fuel consumption and inefficient operation. The Russians address this problem on the LUN by shutting down some of the engines and letting them windmill. The windmill solution results in considerable excess weight and drag and inefficient operation at long distances. The difficult propulsion problem is finding a solution that provides enough thrust for takeoff and also fulfills the overall wingship objective of efficient operation of large vehicles over long distances.

The roadmap explores a combination of technologies which would provide additional thrust at takeoff. They include taxi assisted takeoff by marine engines and power augmented ram. Power augmented ram means directing engine exhaust underneath the wing to provide additional lift. These two options are interdependent in that the thrust required of the aircraft engines at takeoff would depend on how much assistance is provided by the marine engines. The more stressing case for the aircraft engines of no taxi assisted takeoff is assumed so as not to preclude any options.

Power augmented ram would require successful development of thrust vectoring, development of a duct augmentor, and development of wing fuel tanks that are not threatened by the heat generated by the augmentor. Options for thrust vectoring include use of a vectoring nozzle on the engine, but the preferred option would be to mount the engines on a bridge in front of the wings and rotate the bridge at takeoff so that the engine exhaust blows under the wings. This technology is regarded as a structures problem and is excluded from propulsion costs.

Similarly, the development of wing fuel tanks that are safe from combustion by the heat of the augmented exhaust is regarded as a structures problem and is excluded from propulsion costs.

The propulsion section of the roadmap focuses on the modification of high bypass commercial turbofans because they provide a lot of thrust. Any engine selected, regardless of the success of other propulsion technologies, would require several unique features including a fan duct thrust augmentor, the use of cold and hot section coatings and materials substitution for less corrosion, low pressure loss water/inlet air separators, water wash sensors and procedures, etc. The environmental effects of combustion of sea salts would also have to be studied. Such an engine would be unique. Engines that are augmented are designed to fly at supersonic speed and are low bypass mixed flow turbofans. No one is known to have developed an augmentor for a non-mixed flow engine, particularly one with a low pressure ratio fan and very high airflow.

6.1 *Propulsion Estimating Methodology Choices*

The unique development effort described in the section above creates a difficult problem for the estimator. Using new engine developments as the basis for analogies or parametric models is questionable because the roadmap calls for the adaptation of an existing commercial engine. In addition, development costs for commercial engines are difficult to obtain. Most parametric models are based on military engines. Furthermore, most new engines and engine derivatives are developed to increase thrust, reliability, and similar performance characteristics.

Costs are related to the effort required to increase performance. These performance characteristics are reflected in the inputs required in parametric models.

An example of a parametric model that estimates development and production costs of turbine engines was developed by RAND in 1982. The model is based on 16 turbojet and turbofan engines and requires inputs for maximum thrust, mach number, and turbine inlet temperature. The input for thrust seeks to indicate engine size and the cost of test hardware. Turbine inlet temperature is a measure of performance and is a proxy for material content and other parameters. Results are given in the next section on propulsion development costs.

In contrast to new engine developments, the propulsion development for wingship accepts the dry thrust performance of a commercially available engine. It would incur costs to add an augmentor and adapt the engine to the marine environment. Because of the unique nature of this development program, expert judgment is deemed to be the best way to estimate the cost of wingship propulsion development.

6.2 *Propulsion Development Using Expert Judgment*

The roadmap lays out a detailed series of steps for wingship propulsion development. The major steps and their costs according to the propulsion author are summarized below.

1.	Fan augmentor feasibility assessment/rig parametric tests	$2.0 M
2.	Resolve propulsion sizing issues and salt water ingestion hardening planning	1.2 M
3.	Toxic sea salt combustion issues	3.9 - $4.8 M
4.	Acquire candidate engines and salt harden	9.3 M
5.	Salt water ingestion testing	15.4 M
6.	Full scale augmentor rig development	3.5 M
7.	Salt water combustion toxicity mitigation	6.9 M
8.	Augmented engine full scale engineering development	106.0 M
9.	Augmented engine development through limited production decision	120.0 M
10.	*10 engines for preliminary flight test rating*	*100.0 M**
	Total	$370.0 M

* Included in propulsion development costs rather than flight test costs at discretion of the estimator.

The total of $370 million excludes the cost of flight testing the engines.

6.3 *Propulsion Development Using RAND Parametric Model*

The RAND parametric model developed in 1982 was used to check the figure of $370 million. The RAND model includes a method to estimate just the development costs to model qualification tests. These costs do not include the costs of additional improvements once the engine is in production. This method is most appropriate for use here because the number of engines produced for the 400 ton wingship would be small and therefore the ongoing development costs for improvements would be modest compared to a more typical production run. Also, the use of development costs through model qualification tests allows comparison to the estimate provided by the expert which includes costs through preliminary flight rating tests.

The RAND model has the following linear form:

$$MQTDEVCOST = -845.804 + .005(THRMAX) + 249.838(MACH) + .313(TEMP)$$

Inputs for a candidate engine, the Pratt-Whitney JT9D-7R, were 54,750 pounds of thrust, mach 1 (the default value for engines designed for sub-sonic speeds), and 2282 degrees Fahrenheit. The development cost was estimated at $682 million. Again, this estimate is based on new engine development. Its appropriateness for comparison depends on the extent to which wingship propulsion development resembles new engine development.

7. PROPULSION PRODUCTION

Despite the cautions given the discussion in section 6.1. on appropriate estimating methodologies, section 7 includes estimates of the production cost of wingship engines using vendor quotes for commercial engines, expert judgment, and a parametric model.

7.1 *Vendor Quote for Commercial Engine in Same Dry Thrust Class*

As a lower bound, the augmented engines should be no less costly than the commercial engines from which they are derived. The prices of commercial engines are flexible and depend on market conditions. This is confirmed by a 1988 study conducted by TASC and by the experience of the author of the technology roadmap section on propulsion. Allowing for commercial pricing flexibility, a commercial engine in the 50,000 pound thrust class should be obtainable for around $8 million. This vendor quote is based on a small quantity.

The vendor quote of $8 million for a commercial engine actually includes the manufacturer's cost of developing the engine, because in the commercial world manufacturers are not given separate design and production contracts as they are in the military sector. Commercial engine costs therefore include both design and manufacturing costs for the engine. This pricing difference between commercial and military engines confounds the comparison somewhat, but the effect should be small for commercial engines produced in large quantities such as these. A large production run will spread the design costs to a small cost per unit.

7.2 *Expert Judgment on Engine Production Cost*

A second way to estimate the first production cost is by the expert's judgment. The author of the propulsion section of the roadmap estimated that the first ten engines developed for the preliminary flight rating test in full scale engineering development would cost roughly $10 million each. This prototype estimate could be stepped down to a production estimate, but the expert expects that further engine development based on flight test results would be required to increase durability in the marine environment.

7.3 *RAND Parametric Model Estimate of Engine Production Cost*

A third estimate on production costs can be made using the parametric model developed by RAND in 1982. The model was developed from a database of 29 military turbojet and turbofan engines. The inputs for the production model are turbine inlet temperature, maximum thrust, and mach number. The variables were chosen to reflect the engine's material content and size which are thought to drive cost. The CER gives the cumulative average unit production cost of 1000 units:

$$\text{Production Cost} = -2228.140 + .043(\text{THRMAX}) + 243.25(\text{MACH}) + .969(\text{TEMP})$$

The inputs for an engine in the desired thrust class, the Pratt-Whitney JT9D-7R series, are 54,750 pounds of thrust, turbine inlet temperature of 2282 degrees Fahrenheit, and a default value of mach one for an engine designed to operate at subsonic speeds. The model gives an average unit production cost of 1000 units of $4.5 million.

The 1982 RAND study says that a sub-sample of the engines in the RAND database had a learning curve of .93. This learning curve was applied to the 1000th unit to get a first production unit cost of $9.3 million. Four engines plus spares would be required for the first wingship. Thus the first production lot is estimated to be in the range of $9 million each by this parametric method.

7.4 *Propulsion Cost Estimate Summary*

	RAND Model	Vendor Quote	Expert Judgment
Propulsion Development	$682 M	—	$370 M
Propulsion First 6 Units	$54 M	$ 48 M	$60 M

8. AVIONICS

The wingship would require more modest avionics capability than military aircraft. It would require navigation, communication, and flight control equipment. It would not require avionics such as identification friend or foe, electronic countermeasures, target acquisition and fire control, etc., found in most if not all military aircraft.

A wingship would require unique abilities to accurately measure the craft's altitude and attitude over the water, measure sea state, and detect obstacles. The roadmap suggests using a millimeter wave radar to perform the latter two tasks and possibly all four tasks. The Apache Longbow helicopter uses a millimeter wave radar for fire control. The system could conceivably be adapted for navigation over water and integrated into the wingship flight control and navigation system. The production unit cost of the radar is $2-3 million. The costs to adapt it and integrate it would be far greater. Rather than try to build an estimate around one known unique requirement, other approaches were used.

Wingship avionics costs were estimated using the Grumman model and using the C-17 as an analogy. Both approaches were used reluctantly because of the unique but generally more modest requirements for wingship avionics.

8.1 *Grumman Model Estimate of Avionics Development Costs*

CERs based on military aircraft avionics costs must be used with caution to estimate the modest avionics requirements for a wingship to be used in a non-military mission. The Grumman model is derived from military aircraft but has separate CERs for cargo/transport/tanker aircraft and combat types. The preferred CER for cargo/transport/tankers was used. The CER for development requires a number of steps that begin with the unit procurement cost of the 150th unit. The 150th unit cost is derived from the CER below:

$$AVNUPC = (2.0725 * 10^{7})(FFYR)^{2.34}(AVNCWT)^{1.36}$$

FFYR = first flight year
AVNCWT = black box weight in pounds

The wingship's proposed first flight date of 2001 was used. A black box weight of 195 pounds was chosen because it was the lowest figure in the Grumman database and was thought to best reflect the minimal non-military avionics needs of the wingship. The CER gave a 150th unit cost of $132 thousand (FY80).

This cost was backed up a 90 percent learning curve to obtain a first unit cost of $283 thousand (FY80).

The model then calculates a prototype unit cost by this CER:

$$AVPRCT = (2.718)(AVFRST)^{.255}(TOTHST)^{.232}$$

AVFRST = first unit cost
TOTHST = total thrust of un-installed engines

Total thrust is thought to indicate type of aircraft. The prototype unit cost was estimated at $34 million (FY80).

Next, the model calculates avionics development hardware and labor costs. The CER is the same for each cost.

$$AVHDW \text{ or } AVLBR = (6.53)(AVPRCT)^{.387}(PROTO)^{.731}$$

The CER gives a cost of $25.6 million (FY80) for hardware and labor. The total development cost of $51 million (FY80) is escalated to FY95 dollars for a cost of $89 million.

8.2 *C-17 Analogy to Estimate Avionics Development Costs*

A cost data summary report of C-17 was used to provide an upper bound on wingship avionics costs. C-17 avionics included advanced systems unnecessary on the wingship and the comparison should be used cautiously. Unfortunately the report is from early in the program and reflects estimated costs at completion rather than actual costs. Given the cost growth on this program, the actual costs are almost certainly higher. The projected development cost for navigation was $132 million, communications was $12 million, and flight control was $28 million, for a total of $172 million.

8.3 *Grumman Parametric Estimate of Prototype Avionics Costs*

A step in the process of arriving at the avionics design cost was determining the prototype unit cost. That figure can be found in section 8.1 and escalated to FY95 dollars for an estimate of $59 million.

8.4 *Avionics Cost Estimate Summary*

	Grumman Parametric	C-17
Avionics Development	$89 M	$172 M
Avionics First Unit Costs	$59 M	–

9. COST SUMMARY

This section summarizes the cost estimates for the wingship vehicle according to the work breakdown structure categories introduced in section 3.0, and compares the high and low totals to the C-17.

WBS	Low	High	C-17
Airframe Development	$4,512 M	$4,901 M	
Airframe Production Unit	967 M	980 M	
Propulsion Development	370 M	682 M	
Propulsion Production Units	48 M	60 M	
Avionics Development	89 M	172 M	
Avionics Production	59 M	59 M	
Total Vehicle	$6,045 M	$6,854 M	$6,090 M

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These parametric estimates were compared to the initial research and development contract for the C-17, a recently designed military cargo aircraft. The C-17 has an empty weight of 269,000 pounds, and similar material composition (69% aluminum) and speed to the wingship. The C-17 was not part of the databases from which the parametric cost estimating models were developed. The initial development contract for the C-17 was $4,541 million, but has overrun significantly. The program manager's estimate at completion in January, 1994 was over $6 billion in then year dollars. The design effort included one prototype. The C-17 costs include flight testing not estimated here for wingship, but in general include comparable cost elements.

The C-17 incorporates a number of costly design features such as short take off and landing, ability to reverse up a gradient when fully loaded using thrust reversers, ability to survive battle damage, quadruple-redundant fly-by-wire flight control system with mechanical backup, etc. These features would not be designed into the wingship, which would have its own unique design features. No conventional aircraft provides a close analog to the wingship in terms of specific design features. However, the C-17 is the closest analogy in size, type, and time to the wingship and provides a useful sanity check of the parametric estimates. Based on the development and prototype costs of the C-17, the wingship estimates look reasonable.

10. DISCUSSION OF METHODOLOGIES AND CONCLUSION

The wide range of estimates for the 400 ton wingship summarized in the preceding sections suggests areas where estimating methodologies need to be refined for application to wingship technology. There is a particularly broad range of estimates in airframe development and production and propulsion development. This section discusses unique aspects of wingship technology which confound estimating methods intended for conventional aircraft.

The estimates for airframe development differed nearly threefold between the highest and lowest estimate. The 1991 RAND model gave the middle estimate, which was near the lowest number. The RAND model uses aircraft empty weight as an indication of the airframe size and aircraft speed as an indication of the loads on the structure and the complexity of airframe surfaces. Higher speeds are thought to require greater complexity and therefore higher costs. A conventional aircraft with a maximum speed of 400 knots would typically be a cargo aircraft subject to aerodynamic stresses and designed for an ultimate load of around 3.75 g. Assuming that design loads are an important factor in design costs, a model such as the RAND model that is derived from conventional experience would tend to under-estimate the cost of a wingship designed for hydrodynamic stresses and a load of 6 g.

The Grumman model gave the highest and lowest airframe development estimates depending on the input for ultimate design load. The Grumman model requires inputs for maximum gross takeoff weight, total wetted area, and ultimate design load. The combination of these inputs is thought to indicate the size, strength, and complexity of the airframe, and the labor and material costs related to weight. The CERs are power functions. The largest functions for both design and manufacturing costs are for the ultimate load input. The sensitivity of the model to this input is shown by the difference in the design estimate when the model is run with inputs of 4 g and 6 g. The respective costs are $4,512 million and $12,675 million.

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